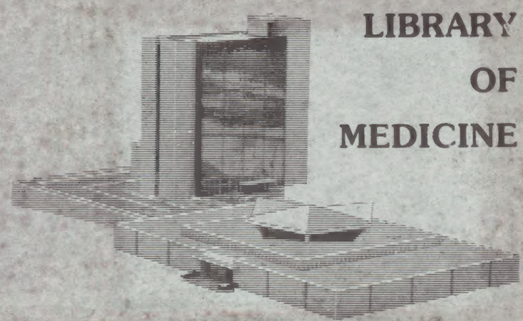
National Research Council [illegible] mittee
" oxygen and anoxia

HANDBOOK
OF
RESPIRATORY DATA
IN
AVIATION

Prepared under the direction of the
SUBCOMMITTEE ON OXYGEN AND ANOXIA
of the
COMMITTEE ON AVIATION MEDICINE
Division of Medical Sciences, National Research Council
Acting for the
COMMITTEE ON MEDICAL RESEARCH
Office of Scientific Research and Development

Washington, D. C.

1944



National Research Council. Subcommittee on "oxygen and anoxia

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INTRODUCTION

It is the purpose of this Handbook to make available in concise and usable form physiological data of value in the study of high altitude physiology and in the design of oxygen equipment for aviators. It has been compiled to meet the needs of the many physiologists, flight surgeons and engineers who, through research, development and training, are endeavoring to make flight at high altitudes safer and more effective.

Much of this material has been collected from published scientific papers and from reports issued by government organizations or service laboratories in the United States, England and Canada. Where significant omissions existed, the necessary information has been obtained by special investigations carried out under contracts with the Committee on Medical Research of the Office of Scientific Research and Development.

Whenever possible, data have been presented graphically in order that they may be more readily used. With each chart there is a brief description explaining its use, together with a statement of the sources from which it has been constructed and a definition of its limitations. Algebraic formulations of the data are also given in many instances, to provide general equations applicable to the solution of specific problems.

The Handbook has been prepared under the direction of the Subcommittee on Oxygen and Anoxia of the National Research Council. But the expeditious publication of this material has required that the authors of the sections which bear their signatures assume responsibility for the data and their interpretation. The Subcommittee is indebted especially to Doctor John R. Pappenheimer for most of the editorial work, for the details of publication and for the preparation of many of the charts.

The rapid development of Aviation Physiology makes it difficult to provide a collection of data such as this, which will be either complete or adequate for more than a brief time. It is, therefore, presented in loose-leaf form so as to facilitate the inclusion of additional material and the elimination of that which may be found inadequate. The Subcommittee will welcome useful additions or corrections from the many workers in this active field of scientific research and application.

THE SUBCOMMITTEE ON OXYGEN AND ANOXIA

Detlev W. Bronk
Chairman

Carl F. Schmidt
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Walter M. Boothby

Eaton MacKay

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T 12 Aug 44

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SECTION P

Physical Data

MEASUREMENT OF BAROMETRIC PRESSURE

ESSAY P

December, 1943

Measurement of Barometric Pressure

Essay P

Mercury Manometers and Barometers. To define pressure in terms of the height of a mercury column standard conditions as to temperature and gravity must be specified. The U. S. standard values are O°C and 980.665 cm/sec^2.

Barometers and manometers divide into two classes: (a) those in which the height of the mercury column is measured directly, as in U-tube manometers and Fortin barometers, and (b) those in which the reading is made essentially only at the top of the column and in which the scale is graduated to take care of the shifting position of the lower mercury surface; examples are fixed cistern manometers and barometers where the scale is foreshortened to compensate for the changing mercury level in the cistern.

For class (a) instruments, the correction to the measured height of the mercury column for deviations from the standard temperature is given in the following table as the percent of the measured height. To obtain the subtractive correction to be applied, multiply the given correction by the column height. In computing the correction the scales are assumed to read correctly at O°C. The temperature effect on the invar scale is assumed to be zero.

Temperature Corrections for
Mercury Manometers and Fortin Barometers

Temperature °C.	Invar scale Correction %	Steel scale Correction %	Brass scale Correction %
0	0	0	0
10	—.18	—.17	—.16
15	—.27	—.26	—.25
20	—.36	—.34	—.33
25	—.45	—.42	—.41
30	—.55	—.51	—.49

For class (b) instruments the temperature error is greater than given in the table, dependent on the relative bores of the cistern and tube.

For both classes of instruments the corrections, expressed as a percentage of the height of the liquid column, corrected for temperature error, to be applied for variation in gravity from the standard value are given below for various latitudes at sea level. Positive values are to be added to the column height at O°C, and negative values subtracted, to obtain the true pressure. The effect of station altitude is +0.01 percent per 1000 feet, an amount ordinarily negligible.

Gravity Corrections for Manometers and Barometers

Latitude degrees	Gravity correction %	Latitude degrees	Gravity correction %
0	—.27	45	0
20	—.21	50	+.04
30	—.14	60	+.13
40	—.05	70	+.20
45	0	90	+.26

Water Manometers. No one temperature has been generally adopted as standard for water manometers. In aeronautics, the standard temperature is generally accepted as 15°C; standard gravity is 980.665 cm/sec^2. On this basis the temperature error in percent of column height is as follows, in which minus corrections are subtracted from, and plus corrections are added to, the indication to obtain the column height at 15°C. In computing the correction the scales are assumed to read correctly at 0°C.

Water Column temperature °C	Temperature Correction Invar Scale %	Steel Scale %	Brass Scale %
10	+.06	+.05	+.04
15	0	—.02	—.03
20	—.09	—.11	—.13
25	—.21	—.24	—.25
30	—.35	—.39	—.40

The gravity corrections are the same as those given for mercury barometers and manometers.

Altimeters. The readings of the altimeter are not affected by changes in the acceleration of gravity.

The effects of temperature changes on the altimeter readings cannot be calculated; they must be determined by test. Present specifications (AN-GG-A-461 dated Sept. 27, 1941) permit the following maximum errors in 50,000 foot altimeters; in general the errors are less, especially for selected altimeters.

Pressure Altitude 1000 feet	Maximum Errors in feet +20°C	—50°C
0	50	100
6	150	250
18	275	550
25	375	750
35	525	1050
40	600	—
50	750	1500

Reference: Smithsonian Metereological Tables, 5th revised edition, 1939. "Barometers and Manometers," Dictionary of Applied Physics, vol. 3, pp. 140-192, 1923.

W. G. B.

Table of Functions

Table P-2

Explanation:

I. *Temperature:* In the United States standard atmosphere a simple altitude-temperature relation is assumed which approximates the yearly average of the observed relation at latitude 40°N. Up to the isothermal layer (35,332 ft.) the relation is given by,

$$T - T_o - aZ = 15 - 0.0019812\ Z \text{ degrees centigrade}$$

where T = air temperature in degrees centigrade.
T_o = standard temperature at sea-level = 15°C.
Z = altitude in feet above sea-level.
a = standard lapse rate of temperature with altitude.
= 0.0019812°C. per foot or 6.5°C. per kilometer.

The mean temperature of the air column below the isothermal layer (T_{ms}) is given by the relation—

$$T_{ms} \text{ (degrees absolute)} = \frac{aZ}{2.303 \log \dfrac{288}{288 - aZ}}$$

II. *Pressure Altitude:* Up to the isothermal layer

$$Z = 221.15\ T_{ms} \log \frac{760}{P_B}$$

where P_B is the barometric pressure (mm. Hg) at altitude Z feet above sea-level.

$$\text{In the isothermal layer } Z = 35{,}332 + 48211 \log \frac{175.9}{P_B}$$

III. Fractions of oxygen to maintain constant pressure of oxygen in inspired air saturated with water vapor at 37°C.

$$F^{SL}_{O_2} = \frac{.209\ (760 - 47)}{P_B - 47}, \quad F^{5000}_{O_2} = \frac{.209\ (632 - 47)}{P_B - 47}, \quad F^{10000}_{O_2} = \frac{.209\ (523 - 47)}{P_B - 47}$$

The fractions of oxygen so calculated are useful in the design of oxygen equipment for maintaining altitude equivalents of 0, 5000 or 10,000 feet. The fractions given are based on physical standards of altitude equivalence and are slightly greater (never more than 5% O_2) than similar fractions calculated from physiological standards based on identity of alveolar gas composition (cf. Chart A-3).

Limitations.

1) The Standard Atmosphere.

In the design of oxygen equipment it may be necessary to consider deviations from the standard atmosphere which occur at different latitudes and in different seasons. Observed values for the altitude and temperature of the tropopause vary from 56,000 feet and —80°C. at the equator to 30,000 feet and —42°C. at the North Pole. In the north temperate zone the seasonal variations of temperature about the standard values given in the table rarely exceed +20° or —30°C. Detailed data concerning the variation of air temperature with altitude may be found in reference (2) cited below.

2) Fractions of Oxygen in Inspired Air.

Use of these oxygen fractions in relation to quantitative physiological investigations at altitude should be considered only after examination of the assumptions implicit in the equations given above. A discussion of these assumptions is given in Essay A, Section V.

Sources: 1) W. G. Brombacher, N. A. C. A. Report #538.
2) E. M. Walsh, Airesearch Mfg. Co. Report #AEE-90-R.
3) W. M. Boothby, Mayo Aero Medical Unit.

F. B., Jr. and J. R. P.

TABLE P-2

TABLE OF FUNCTIONS

Based on U. S. Standard Atmosphere

	Altitude (feet)	Temperature°C	P.S.I.	mm.Hg	P_B-47 mm.Hg	Based on Physical Standard of Constant Po_2 in Saturated Inspired Gas		
						Fo_2^{SL}	Fo_2^{5000}	Fo_2^{10000}
	0	15.0	14.69	760.0	713.0	0.21	.17	.14
	500	14.0	14.43	746.4	699.4	0.21	.18	.14
	1000	13.0	14.17	732.9	685.9	0.22	.18	.14
	1500	12.0	13.91	719.7	672.7	0.22	.18	.15
	2000	11.0	13.66	706.6	659.6	0.23	.19	.15
0	2500	10.0	13.41	693.8	646.8	0.23	.19	.15
	3000	9.1	13.17	681.1	634.1	0.24	.19	.16
	3500	8.1	12.93	668.6	621.6	0.24	.20	.16
	4000	7.1	12.69	656.3	609.3	0.25	.20	.16
	4500	6.1	12.45	644.2	597.2	0.25	.21	.17
	5000	5.1	12.22	632.3	585.3	0.25	.21	.17
	5500	4.1	12.00	620.6	573.6	0.26	.21	.17
	6000	3.1	11.77	609.0	562.0	0.27	.22	.18
	6500	2.1	11.55	597.6	550.6	0.27	.22	.18
	7000	1.1	11.34	586.4	539.4	0.28	.23	.19
5	7500	0.1	11.12	575.3	528.3	0.28	.23	.19
	8000	-0.8	10.91	564.4	517.4	0.29	.24	.19
	8500	-1.8	10.70	553.7	506.7	0.29	.24	.20
	9000	-2.8	10.50	543.2	496.2	0.30	.25	.20
	9500	-3.8	10.30	532.8	485.8	0.31	.25	.20
	10000	-4.8	10.10	522.6	475.6	0.31	.26	.21
	10500	-5.8	9.91	512.5	465.5	0.32	.26	.21
	11000	-6.8	9.72	502.6	455.6	0.33	.27	.22
	11500	-7.8	9.53	492.8	445.8	0.33	.27	.22
	12000	-8.8	9.34	483.3	436.3	0.34	.28	.23
10	12500	-9.8	9.16	473.8	426.8	0.35	.29	.23
	13000	-10.8	8.98	464.5	417.5	0.36	.29	.24
	13500	-11.7	8.80	455.4	408.4	0.37	.30	.24
	14000	-12.7	8.63	446.4	399.4	0.37	.31	.25
	14500	-13.7	8.53	437.5	390.5	0.38	.31	.25
	15000	-14.7	8.29	428.8	381.8	0.39	.32	.26
	15500	-15.7	8.12	420.2	373.2	0.40	.33	.27
	16000	-16.7	7.96	411.8	364.8	0.41	.34	.27
	16500	-17.7	7.80	403.5	356.5	0.42	.34	.28
	17000	-18.7	7.64	395.3	348.3	0.43	.35	.29
15	17500	-19.7	7.49	387.3	340.3	0.44	.36	.29
	18000	-20.7	7.33	379.4	332.4	0.45	.37	.30
	18500	-21.7	7.18	371.7	324.7	0.46	.38	.31
	19000	-22.6	7.03	364.0	317.0	0.47	.39	.31
	19500	-23.6	6.89	356.5	309.5	0.48	.40	.32
	20000	-24.6	6.75	349.1	302.1	0.49	.41	.33
	20500	-25.6	6.61	341.9	294.9	0.51	.42	.34
	21000	-26.6	6.47	334.7	287.7	0.52	.43	.35
	21500	-27.6	6.33	327.7	280.7	0.53	.44	.35
	22000	-28.6	6.20	320.8	273.8	0.55	.45	.36
20	22500	-29.6	6.07	314.1	267.1	0.56	.46	.37
	23000	-30.6	5.94	307.4	260.4	0.57	.47	.38
	23500	-31.6	5.82	300.9	253.9	0.59	.48	.39
	24000	-32.5	5.69	294.4	247.4	0.60	.50	.40
	24500	-33.5	5.57	288.1	241.1	0.62	.51	.41
	25000	-34.5	5.45	281.9	234.9	0.63	.52	.42
	25500	-35.5	5.33	275.8	228.8	0.65	.54	.44
	26000	-36.5	5.22	269.8	222.8	0.67	.55	.45
25	26500	-37.5	5.10	263.9	216.9	0.69	.57	.46
	27000	-38.5	4.99	258.1	211.1	0.71	.58	.47
	27500	-39.5	4.86	252.5	205.5	0.72	.60	.49

TABLE OF FUNCTIONS

Based on U. S. Standard Atmosphere

	Altitude (feet)	Temperature°C	P.S.I.	mm.Hg	P_B-47 mm.Hg	Based on Physical Standard of Constant Po_2 in Saturated Inspired Gas		
						Fo_2^{SL}	Fo_2^{5000}	Fo_2^{10000}
	28000	-40.5	4.77	246.9	199.9	0.75	.61	.50
	28500	-41.5	4.67	241.4	194.4	0.77	.63	.51
	29000	-42.5	4.56	236.0	189.0	0.79	.65	.53
	29500	-43.4	4.46	230.7	183.7	0.81	.67	.54
	30000	-44.4	4.36	225.6	178.6	0.84	.69	.56
	30500	-45.4	4.26	220.5	173.5	0.86	.71	.57
	31000	-46.4	4.17	215.5	168.5	0.89	.73	.59
	31500	-47.4	4.07	210.6	163.6	0.91	.75	.61
	32000	-48.4	3.98	205.8	158.8	0.94	.77	.63
30	32500	-49.4	3.89	201.0	154.0	0.97	.80	.65
	33000	-50.4	3.80	196.4	149.4	1.00	.82	.67
	33500	-51.4	3.71	191.8	144.8		.85	.69
	34000	-52.4	3.62	187.4	140.4		.87	.71
	34500	-53.4	3.54	183.0	136.0		.90	.73
	35000	-54.3	3.46	178.7	131.7		.93	.76
	35332	-55.0	3.40	175.9	128.9		.95	.77
	35500	-55.0	3.37	174.5	127.5		.96	.78
	36000	-55.0	3.29	170.4	123.4		.99	.81
	36100	-55.0	3.28	169.6	122.6		1.00	.81
	36500	-55.0	3.22	166.4	119.4			.83
	37000	-55.0	3.14	162.4	115.4			.86
35	37500	-55.0	3.07	158.6	111.6			.90
	38000	-55.0	3.00	154.9	107.9			.92
	38500	-55.0	2.92	151.2	104.2			.95
	39000	-55.0	2.85	147.6	100.6			.99
	39500	-55.0	2.79	144.1	97.1			1.00
	40000	-55.0	2.72	140.7	93.7			
	40500	-55.0	2.66	137.4	90.4			
	41000	-55.0	2.59	134.2	87.2			
	41500	-55.0	2.53	131.0	84.0			
	42000	-55.0	2.47	127.9	80.9			
40	42500	-55.0	2.42	124.9	77.9			
	43000	-55.0	2.36	122.0	75.0			
	43500	-55.0	2.30	119.1	72.1			
	44000	-55.0	2.25	116.3	69.3			
	44500	-55.0	2.19	113.5	66.5			
	45000	-55.0	2.14	110.8	63.8			
	45500	-55.0	2.09	108.2	61.2			
	46000	-55.0	2.04	105.7	58.7			
	46500	-55.0	2.00	103.2	56.2			
	47000	-55.0	1.95	100.7	53.7			
45	47500	-55.0	1.90	98.38	51.38			
	48000	-55.0	1.86	96.05	49.05			
	48500	-55.0	1.81	93.79	46.79			
	49000	-55.0	1.77	91.57	44.57			
	49500	-55.0	1.73	89.41	42.41			
	50000	-55.0	1.69	87.30	40.30			
	51000	-55.0	1.61	82.22	36.22			
	52000	-55.0	1.53	79.34	32.34			
	53000	-55.0	1.46	75.64	28.64			
	54000	-55.0	1.39	72.12	25.12			
50	55000	-55.0	1.33	68.76	21.76			
	56000	-55.0	1.27	65.55	18.55			
	57000	-55.0	1.21	62.49	15.49			
	58000	-55.0	1.15	59.58	12.58			
	59000	-55.0	1.10	56.80	9.80			
	60000	-55.0	1.05	54.15	7.15			

POSITIVE PRESSURES REQUIRED TO ATTAIN
STATED EFFECTIVE ALTITUDES

CHART P-3

November, 1943

Positive Pressures Required to Attain Stated Effective Altitudes

Chart P-3

This nomogram provides a rapid means for calculating the pressure differential required to maintain any given effective altitude at any given altitude. The chart is useful for problems involving pressurized equipment of all types. It contains no physiological data. It is constructed from the relation—

Effective pressure (altitude) = Ambient pressure (altitude) + Applied pressure differential.

Use of the chart is illustrated by the following examples:

1) A pressurized aircraft is flying at 20,000 feet. What pressure is required to maintain the cabin at an effective altitude of 12,000 feet?—A straight line drawn through 20,000 ft. and 12,000 ft. (sample, Range 1) intersects the Applied Pressure axis at 2.75 lbs/in². *Ans.*

2) A pressure of 8″ of water is applied to the mask of an individual flying at 44,000 feet. What is the effective pressure altitude inside the mask?—A straight line drawn through 44,000 feet and 8″ of water (sample on Range #2) intersects the Effective Altitude axis at 41,500 feet. *Ans.*

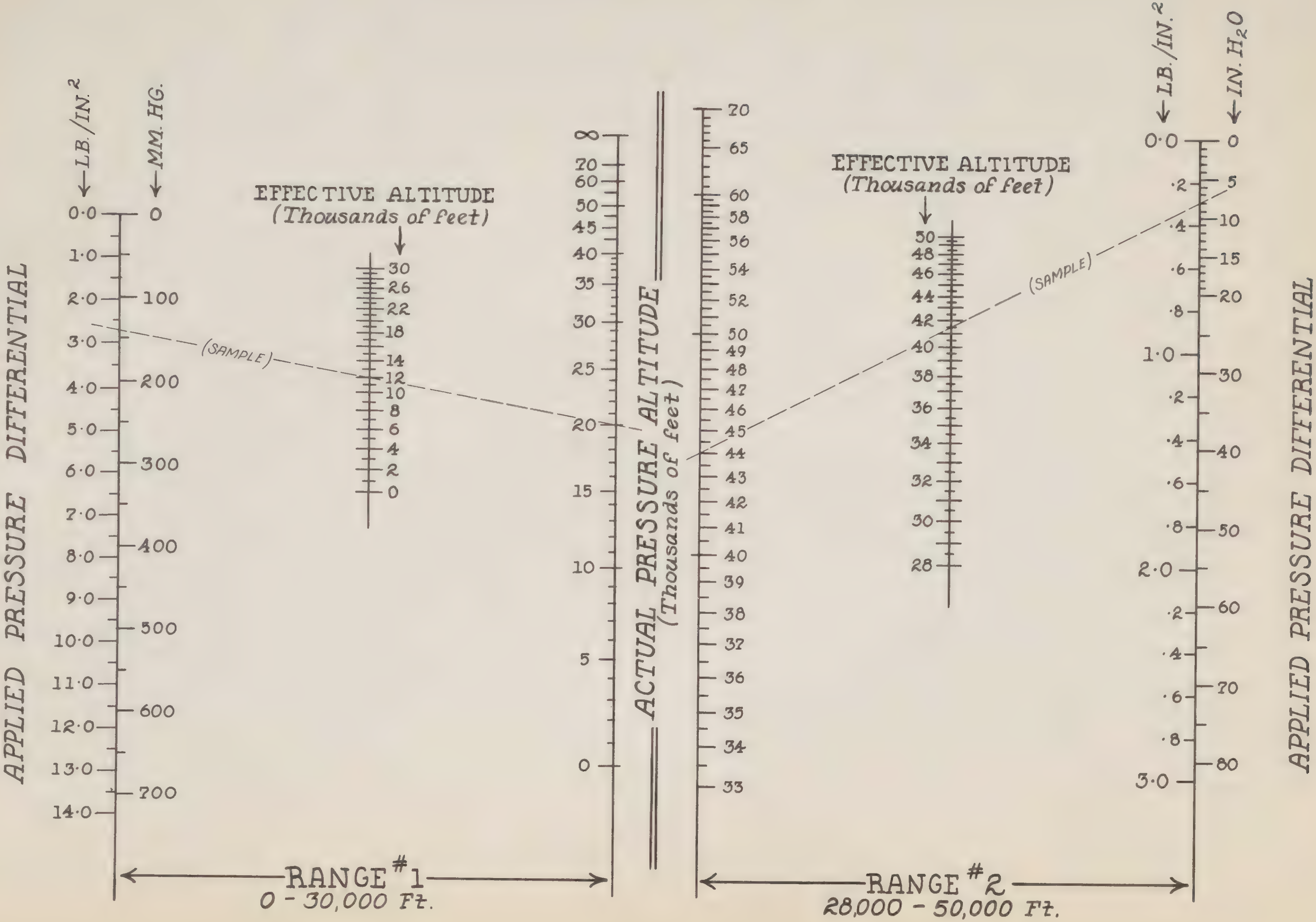
Limitations:

It should be emphasized that the nomogram is based solely on physical data and that the "effective pressure altitudes" obtained from it do not necessarily correspond with "physiologically equivalent altitudes." This limitation is especially important in connection with pressure breathing where the application of pressure in the mask may produce physiological changes in addition to those brought about by the change of "effective pressure altitude."

Source: N. A. C. A. Report #538

J. R. P.

POSITIVE PRESSURES REQUIRED TO ATTAIN STATED EFFECTIVE ALTITUDES



Properties of Oxygen

Table P-4

I. *Specific Weight* (density) of gaseous oxygen subjected to standard gravity at one atmosphere pressure.

Table A

Temperature °C	grams/liter	lbs./cu. ft.	lbs./cu. inch x 10^4
—40	1.674	.1045	.604
—30	1.605	.1002	.579
—20	1.542	.0962	.557
—10	1.484	.0926	.536
*0	1.429	.0892	.516
10	1.378	.0861	.498
20	1.331	.0832	.481
30	1.287	.0804	.465
40	1.246	.0778	.450

* values at 0 degrees from Int. Crit. Tables; other values computed.

II. *Weight of Oxygen* in supply cylinders at pressures greater than one atmosphere.

$W = P \times d \times V/K$

where P = gage pressure of cylinder in atmospheres.
W = weight of oxygen in lbs.
d = specific weight of oxygen at one atmosphere and at temperature at which P is measured (Table A, above).
V = volume of cylinder in cubic inches.
K = compressibility factor given in Table B below.

Table B

Pressure lbs./sq. inch	atmospheres	K 0°C.	20°C.
450	30.6	.973	.981
900	61.3	.946	.962
1800	122.5	.915 (approx.)	.938 (approx.)

III. *Weight* in lbs./hr. of an oxygen flow of one liter per minute at 0°C. and at ambient pressure.

Altitude (thousands of ft.)	0	10	20	25	30	35	40
Oxygen, lbs./hr.	.189	.130	.086	.070	.056	.044	.035

IV. *Oxygen from Tank Supply* required to produce stated fractions (Fo_2) of oxygen in air-oxygen mixtures.

Fraction of oxygen from tank = $(Fo_2 - .21)/.79$

Fraction of oxygen in mixture	.21	.30	.40	.50	.60	.70	.80	.90	1.00
Fraction of total volume drawn from tank o_2 supply	0	.11	.24	.37	.49	.62	.75	.87	1.00

V. *Miscellaneous Properties of Liquid and Solid Oxygen*

Melting point —218.4°C.
Boiling point at 760 mm. Hg = —183°C.
at 493 mm. Hg = —187°C.
at 162 mm. Hg = —195.5°C.

Specific Weight at —183°C. = 1.14 g/cc. = 71.2 lb./cu. ft. = .0412 lb./cu. inch.

One liter of liquid oxygen weighs 1140 grams or 2.52 lbs. It is equivalent to 797 liters of gaseous oxygen measured at 0°C. at a pressure of 1 atmosphere.

One pound of liquid oxygen yields 317 liters of gaseous oxygen at 0°C., 1 atmosphere.

Heat of Vaporization at —183° C. = 50.9 cal./gram, at —188°C. = 52.0 cal./gram.

Specific Heat liquid oxygen at —200°C. = 0.394 cal./gram
solid oxygen at —222°C. = 0.336 cal./gram

Surface Tension at —183°C. = 13.2 dynes/cm.

W. G. B.

SECTION A

Composition of Respiratory Gases

CALCULATIONS RELATING TO THE COMPOSITION OF RESPIRATORY GASES

ESSAY A

Calculations Relating to the Composition of Respiratory Gases

Essay A

Purpose: To present detailed derivation of equations used to construct Charts A-2, A-3, A-4, A-5 and M-2. Knowledge of the contents of this essay is not essential to the practical application of the charts.

Contents

I. *Definition of Symbols*

P_B = barometric pressure
P_X = pressure of gas X in inspired gas
P'_X = pressure of gas X in expired gas
pX = pressure of gas X in alveolar gas
R. Q. = metabolic respiratory quotient
F_X = fraction of gas X in dry inspired gas
$F_{O_2}^{SL}$ = fraction of oxygen in inspired gas required to maintain Po_2 in any portion of in lung gases equal to that at sea level when breathing air. Similar designation for 5000 feet would be $F_{O_2}^{5000}$
* = specific for quantities associated with breathing air.

II. *Introduction*

In principle it is obvious that the composition of exhaled gas can be calculated in terms of the composition of inhaled gas and any additions or subtractions of molecules by the body. It is the object of this essay to develop equations relating the composition of dry inspired gas containing oxygen and nitrogen to the composition of any portion of this gas after it has been saturated with water vapor and has exchanged oxygen for carbon dioxide in the body. The derived equations are employed to construct Charts A-2, A-3, A-4, A-5 and M-2. A simplified form of the general equation which considers only the effect of water vapor on the composition of inspired gas is employed to calculate the oxygen content of inspired gas that supply systems should deliver at altitude (Table P-2).

In the following derivations several terms are frequently used which require special definition.

1) *Steady state of respiratory exchange.*† The steady state of exchange is such that following each inspiration there is expired a volume of gas which leaves the volume and composition of gas remaining in the lungs and trachea identical with that at the end of the preceding expiration. In practice this condition rarely applies to successive respiratory cycles, but is characteristic of the volume and composition of the respiratory gases when these are averaged over reasonable intervals of time under constant physiological conditions.

2) *The Respiratory Quotient, R. Q.* The metabolic processes of the body are such that in a steady state of respiratory exchange the number of molecules of CO_2 given off by the blood is less than the number of molecules of O_2 absorbed per unit time and the ratio of these two quantities is known as the metabolic respiratory quotient. The value of this ratio is ordinarily calculated from the measured difference between the composition of dry inspired air and gas which has been expired during a steady state period of respiratory exchange. When a particular portion of gas exhaled during part of a single expiration is analyzed, the ratio of CO_2 added to oxygen removed is not necessarily equal to the average metabolic R. Q. The value of this ratio for alveolar air samples calculated from the average data of Chart A-1 by equation 8 is about 0.85. This is comparable with the nominal value of 0.82 for the average metabolic R. Q. Therefore, in the calculations relating to the composition of alveolar air samples collected as described in Chart A-1 the metabolic R. Q. may be employed.

† In Section VI the non-steady state of respiratory exchange is discussed.

3) *Alveolar Gas.* In the following derivation the term *alveolar gas* is employed to designate a sample of expired gas obtained as described in the legend of Chart A-1. No attempt is made to define the relations between the partial pressures of gases in such a sample and the partial pressures of gases in the arterial blood because this subject is unsettled at present and is being reinvestigated. It is important to recognize, however, that estimations of equivalent altitudes based on equivalence of alveolar gas composition agree closely with similar estimations made on the basis of equivalent arterial oxygen saturations as determined experimentally (Charts A-2, B-4).

III. *Derivation* †

If the inspired gas contains only oxygen and nitrogen,†† then by definition—

1)
$$R.\,Q. = \frac{M'_{CO_2}}{M_{O_2} - M'_{O_2}}$$

Where: M'_{CO_2} = number of CO_2 molecules exhaled per breath.
M'_{O_2} = number of O_2 molecules exhaled per breath.
M_{O_2} = number of O_2 molecules inhaled per breath.

The only limitation of this definition of the metabolic R. Q. is that a steady state of respiratory exchange is assumed.

The number of carbon dioxide molecules in the expired air can be expressed in terms of their partial pressure and the volume of expired gas V′. A similar law holds for the oxygen content of inspired and expired gas. The volumes of gas (V and V′) considered, are not identical even when dry because the amount of CO_2 added is not equal to amount of O_2 taken away. Thus—

2)
$$M'_{CO_2} = \frac{P'_{CO_2}}{RT} \times V'$$

$$M'_{O_2} = \frac{P'_{O_2}}{RT} \times V'$$

$$M'_{N_2} = \frac{P_{N_2}}{RT} \times V'$$

$$M_{O_2} = \frac{P_{O_2}}{RT} \times V$$

$$M_{N_2} = \frac{P_{N_2}}{RT} \times V$$

Since nitrogen is an inert gas the number of molecules exhaled equals the number inhaled.

$$M_{N_2} = M'_{N_2}$$

Therefore—

3)
$$\frac{P'_{N_2}}{P_{N_2}} = \frac{V_{N_2}}{V'_{N_2}}$$

The relations (2) and (3) can be substituted in equation 1 to give equation (4).

4)
$$R.\,Q. = \frac{P'_{CO_2}}{P_{O_2}\dfrac{P'_{N_2}}{P_{N_2}} - P'_{O_2}}$$

The various equations to be derived in the several forms in which they have actually been employed are special cases of equation (4).

† This derivation contains the essential features of similar derivations by A. C. Burton, Toronto, Canada, D. B. Dill, War Department Report #Exp-M-653-103A, W. A. Wildhack, J. Aeronautical Sc., Vol. 9, 1942, J. S. Gray, Report #131, School of Aviation Medicine, Randolph Field, and Major J. Berkson, Office of The Air Surgeon, Washington, D. C.

†† The presence of 0.04 percent CO_2 in the inspired gas will not change the values calculated from these equations to an important degree. Equations including inspired CO_2 will be given in a separate section. If it is desired to estimate R. Q. to three figures the .04 percent CO_2 in air must be employed.

IV. *Special Applications*

1. *To calculate R. Q. from Analysis of Expired Gas.*

Divide each member of the right side of equation (4) by the barometric pressure (P_B) and introduce the definition,

$$Fx = \frac{Px}{P_B}$$

The equation becomes—

$$\text{5)} \qquad R.\,Q. = \frac{F'_{CO_2}}{F_{O_2}\dfrac{F'_{N_2}}{F_{N_2}} - F'_{O_2}}$$

This is the form usually employed to calculate R. Q. from analysis of expired gas.

2. *To calculate the R. Q. from analysis of alveolar gas.*

The results of alveolar gas analysis are usually presented in terms of the partial pressures of oxygen and of CO_2 so the equation is employed in form (4). Here the symbols refer to that portion of expired gas which is defined as alveolar gas. Since the partial pressures of nitrogen are always obtained by subtraction from the barometric pressure, it is convenient to introduce this change explicitly. Thus for dry inspired gas—

$$P_{N_2} = P_B - P_{O_2}$$

and for the moist alveolar gases containing oxygen and carbon dioxide—

$$pN_2 = P_B - pCO_2 - pO_2 - pH_2O$$

The nitrogen pressures differ since the inspired dry gas is saturated at 37° within the lungs as well as being affected by exchanged CO_2 and O_2. The quantity pH_2O is assumed to be 47 mm. Hg. for alveolar gas at body temperature. Making these substitutions

$$\text{6)} \qquad R.\,Q. = \frac{(P_B - P_{O_2})\, pCO_2}{P_{O_2}\,(P_B - 47 - pCO_2) - P_B pO_2}$$

The composition of inspired gas is usually given as the fraction of oxygen in the dry gas. Thus substituting the definition

$$F_{O_2} = \frac{P_{O_2}}{P_B}$$

equation (6) becomes

$$\text{7)} \qquad R.\,Q. = \frac{(1 - F_{O_2})\, pCO_2}{F_{O_2}(P_B - pH_2O - pCO_2) - pO_2}$$

If the inspired gas is air, this equation becomes:

$$\text{8)} \qquad R.\,Q. = \frac{0.791\, pCO_2}{0.209\,(P_B - 47 - pCO_2) - pO_2}$$

The calculation of the R. Q. from analysis of alveolar gas is done by substitution in equation (8).

3. *To Calculate Alveolar Oxygen Tensions From Knowledge of the Composition of Inspired Gas.*

$$\text{9)} \qquad pO_2 = F_{O_2}\,(P_B - 47) - pCO_2\,\frac{1 - F_{O_2}\,(1 - R.\,Q.)}{R.\,Q.}$$

4. *To Calculate the Oxygen Composition of Inspired Dry Gas Required to Maintain Constant Alveolar pO_2 at Altitude.*

$$\text{10)} \qquad F_{O_2} = \frac{pO_2 + \dfrac{pCO_2}{R.\,Q.}}{P_B - 47 - pCO_2 + \dfrac{pCO_2}{R.\,Q.}}$$

The use of this equation is illustrated in Section V and in Chart A-4.

5. *To Calculate Altitudes Breathing Gas Mixtures Physiologically Equivalent to Altitudes Breathing Air.*

Another use (see Chart A-2) is to calculate altitudes when breathing a gas mixture that are physiologically equivalent to various altitudes when breathing air.

Equivalent altitudes are defined by

11) $$\text{a) } pO_2 = pO^*_2 \qquad \text{b) } pCO_2 = pCO^*_2$$

For this purpose the quantities associated with air breathing may be marked with an asterisk: Thus—

12) $$pO^*_2 + pCO^*_2 \frac{1 - 0.209\,(1 - R.Q.)}{R.Q.} = 0.209\,(P^*_B - 47)$$

For other gas mixtures

13) $$pO_2 + pCO_2 \frac{1 - Fo_2\,(1 - R.Q.)}{R.Q.} = Fo_2\,(P_B - 47)$$

Using relation (a) equations *12* and *13* may be combined, thus

14) $$Fo_2\,(P_B - 47) - pCO_2 \frac{1 - Fo_2\,(1 - R.Q.)}{R.Q.} = 0.209\,(P^*_B - 47) - pCO^*_2 \frac{1 - 0.209(1 - R.Q.)}{R.Q.}$$

From relation (b)

15) $$P_B = \frac{0.209}{Fo_2} P^*_B + \frac{(Fo_2 - 0.209)}{Fo_2} 47 - pCO^*_2 \frac{(Fo_2 - 0.209)}{Fo_2} \times \frac{(1 - RQ)}{R.Q.}$$

The equation (4) is therefore of great usefulness in analyzing relations between composition of alveolar gas and that of the inspired gas at any altitude. But the same equation is equally applicable to calculation based upon analyses of total expired gas. In brief, when employing the equation to calculate alveolar pO_2 we need to know the alveolar pCO_2 or vice versa. This is the sole unique connection between symbols in the equation and the alveolar gas composition. Correspondingly when the value of $P'co_2$ in expired gas is used the value of $P'o_2$ in expired gas is calculated.

V. *Approximate Calculations for Regulator Design*

The equation (10) can be simplified for the purpose of specifying the composition of gas to be supplied by an oxygen supply system. These simplifications are desirable for two principal reasons. First, the variation in alveolar pO_2 and pCO_2 observed in the population is considerable, making necessary the use of statistical values for these quantities. Second, oxygen supply systems (unlike the mask) are not designed for the individual but must be constructed with a sufficient factor of safety to fit the population.

At sea level the respiration is adjusted to maintain an approximately constant alveolar carbon dioxide pressure. Though experiments show this value to vary from 35-45 mm. Hg in the population, by far the largest number have a value close to 40 mm. Hg. Experiment also shows that the metabolic R. Q. calculated from (8) is about 0.85 for the analyses reported in Chart A-1. These two nominal values substituted into equation (9) give a corresponding average pO_2 of 104 mm. Hg. Therefore, to maintain the alveolar oxygen pressure equal to that at sea level the fraction of oxygen in inspired air is given by

16) $$F^{SL}_{O_2} = \frac{151}{P_B - 40}$$

Evaluation of available data on alveolar CO_2 analyses (see Chart A-2) indicates that a man breathing air at 5000 feet altitude will have, on the average, an alveolar pCO_2 of 38 mm. Hg. Using this value in equation (9) indicates a corresponding pO_2 of 79 mm. of Hg. To maintain this oxygen pressure in the alveoli at higher altitudes the fraction of oxygen in the inspired gas is

17) $$F^{5000}_{O_2} = \frac{124}{P_B - 40}$$

At an altitude of 10,000 feet breathing air the experimental average pCO_2 is 35 mm. Hg. For this condition the alveolar pO_2 is 59 mm. Hg. To maintain these conditions at altitude

18) $$F^{10000}_{O_2} = \frac{101}{P_B - 41}$$

The numerical values appearing in Equations 16, 17 and 18 depend upon average values of R. Q. and pCO_2 determined experimentally on a large number of individuals (Chart A-1). The equations therefore represent approximations based on the best data available at the present time, but they are subject to such revision as may be indicated by further data.

Another form of approximation leads to a practical standard suggested by Dr. W. M. Boothby. If the R. Q. is assumed to be 1.0, then equation (14) becomes

19) $$Fo_2\ (P_B - 47) = .209\ (P_B{}^* - 47)$$

The quantity on the right side of this equation is the oxygen tension Po_2 in saturated inspired gas when breathing air. Thus

$$Po_2 = 0.2094\ (P_B{}^* - 47)$$

Therefore, according to these assumptions, the Fo_2 values calculated from (19) depend only upon physical quantities and the oxygen required at altitude is defined in terms of the Po_2 in inspired gas saturated with water vapor at 37°C.

From (19) we have—

20) $$F^{SL}_{O_2} = .209\ (760 - 47)/P_B - 47 = \frac{149.3}{P_B - 47}$$

21) $$F^{5000}_{O_2} = \frac{122.6}{P_B - 47}$$

22) $$F^{10000}_{O_2} = \frac{99.6}{P_B - 47}$$

The numerical relations between the two methods of approximation are shown in Chart A-3. The differences are not sufficiently large to be of practical importance in present-day regulator design although they may be of importance in the interpretation of research work involving equivalent altitudes (Chart A-2). Fo_2 values based on equations 20, 21 and 22 are given in Table P-2. A summary of the approximate equations is given in § VII.

VI. *The Non-Steady State of Respiratory Exchange*

In developing the equations in Section II it was stressed that the results applied only to steady states of respiratory exchange. This restriction is necessary in order to permit a definite interpretation of the quantity R. Q. introduced in equation 1, page 2. In the steady state this quantity may be identified with the metabolic respiratory quotient, but in the non-steady state it is merely the ratio of the quantity of carbon dioxide in expired air to the difference in oxygen content of expired and inspired air. During a non-steady state of respiratory exchange, when the pCO_2 and pO_2 are changing with time, this ratio may be designated simply as R to distinguish it from the true R. Q. With this change in interpretation the derivation can be made as before. However, the relations between pCO_2 and pO_2 are now between instantaneous values of quantities which are continuously changing as the respiratory exchange passes from one steady state to another.

The limited data available indicate that the transient change from one steady state of respiratory exchange to another takes approximately 45 minutes. During this time the value of R rises rapidly to a maximum and falls again to its original value, as indicated in Table I.

Changes in Alveolar Tension During One Hour Stay at 18,000 Feet

(Lutz & Schneider)
(Amer. J. Physiol. 50, 280, 1919)

Minutes at 18,000 ft.	pO_2	pCO_2	Calculated R
0	38.5	30.8	0.98
10	36.5	30.4	0.88
20	35.2	31.5	0.89
30	35.0	31.0	0.86
40	33.9	30.3	0.81
50	34.4	29.1	0.78
60	35.1	29.0	0.80

In research on respiratory problems these transient phenomena are of utmost importance because many experiments have been carried out in too short a time to achieve steady state conditions. The calculation of R, by equation (7) offers a convenient criterion for stating that a set of data apply to steady states of respiratory exchange. The data from the control period of the experiment provide a reference value of R. The subject will be in a new steady state following some change when R again approaches this control value. Thus in the

experiment illustrated in Table I, R has returned to the control level of .80 in about 40 minutes. In this instance the analyses were made on alveolar air. As a general control measure of this sort the values of R calculated from a series of expired air samples would serve the same purpose in experiments not specifically concerned with collecting alveolar gas samples.

The deviations from normal respiration expected in aviation are hyperventilation from excitement or mild anoxia. This raises the pO_2 in the alveolar gas by lowering the pCO_2. Therefore, if the composition of inspired gas has been set at a value which insures an adequate alveolar pO_2 at a given altitude during normal respiration the change during transient hyperventilation will be to increase this pO_2.

Thus far only short-time transient changes have been considered since these are probably most important in aviation. If mild anoxia lasted a week or more, the degree of hyperventilation would increase very gradually. This prolonged adjustment to altitude, called acclimatization, is associated with rather insignificant changes in composition of alveolar gas relative to those accomplished during the first hour of exposure.

VII. *Summary of Equations*

General Equations (Definition of Symbols on Page 1)

Reference in essay

A) $$pO_2 = Fo_2\,(P_B - 47) - pCO_2\,\frac{1 - Fo_2\,(1 - R.Q.)}{R.Q.}$$ Eq. 9, p. 3

B) $$Fo_2 = \frac{pO_2 + \dfrac{pCO_2}{R.Q.}}{P_B - 47 + pCO_2\left(\dfrac{1 - R.Q.}{R.Q.}\right)}$$ Eq. 10, p. 3

C) $$P_B = \frac{.209}{Fo_2}\left[P_B^* - 47 - pCO_2^*\left(\frac{1 - R.Q.}{R.Q.}\right)\left(\frac{Fo_2 - .209}{.209}\right)\right] + 47$$ Eq. 15, p. 4

Approximate Equations

By "Maximum error" in the following table is meant the largest discrepancy between the results of direct substitution in the approximate equations and values obtained from Equations A), B) and C), where R. Q. is taken = 0.85, and the pCO_2 values of Chart A-2 are used. The "maximum errors" refer to altitudes breathing air (denoted by asterisk) up to 20,000 feet. These errors may be exceeded at higher altitudes.

Quantity	Simple graphical solution with best fit	Maximum error	Equations based on physical standard: equal oxygen pressures in inspired gas, 37°C., saturated	Maximum error
Fraction of oxygen in inspired air to maintain stated equivalent altitude	D) $F_{O_2}^{SL} = \frac{150}{P_B - 40}$	.01	K) $F_{O_2}^{SL} = \frac{149}{P_B - 47}$	.05
	E) $F_{O_2}^{5000} = \frac{125}{P_B - 40}$	.01	L) $F_{O_2}^{5000} = \frac{123}{P_B - 47}$	.05
	F) $F_{O_2}^{10000} = \frac{100}{P_B - 40}$	.01	M) $F_{O_2}^{10000} = \frac{100}{P_B - 47}$	.05
Alveolar oxygen pressure, breathing air (mm. Hg)	G) $pO_2^* = .185\,P_B - 37$	2 mm.	——	
Barometric pressure breathing oxygen equivalent to given barometric pressure breathing air (mm. Hg)	H) $P_B = .206\,P_B^* + 34$	1 mm.	N) $P_B = .209\,(P_B^* - 47) + 47 = .209\,P_B^* + 37$	5 mm.
Altitude breathing oxygen equivalent to given altitude breathing air (in feet)	J) Alt = 33,700 + .6 Alt*	200 feet	O) Alt = 33,000 + .6 Alt*	800 feet

F. B., Jr.

Alveolar Oxygen and Carbon-Dioxide Pressures While Breathing Air at Altitude

Chart A-1

The data in this chart were obtained by analyses of the fractions of CO_2 and O_2 in alveolar air samples collected over mercury by the Haldane-Priestley method of sampling aided by a specially constructed valve. In the average values indicated by an open circle there are 1025 observations at various elevations, 836 of which were obtained on 30 male and 189 on 5 female subjects. In addition 288 observations have been put on the chart which were obtained by various other methods of obtaining alveolar air samples, both at rest and at work. These are indicated on the chart by separate signs. The alveolar air samples were obtained as a rule in the forenoon after a normal breakfast and less frequently in the afternoon after an average lunch.

On an average flight alveolar samples were obtained usually on the way up at six or seven different elevations although occasionally they were obtained on the way down after a rapid ascent. The runs lasted therefore about three to three and a half hours. Before the first alveolar air sample was taken ten minutes were allowed to elapse after arrival at each elevation for the subject to become partially stabilized to that altitude. A second alveolar air sample at each altitude was taken after another five minutes. The subjects were at sitting rest and care was taken that they remain quiet without talking during the preliminary and alveolar air sampling periods.

Curve A

Curve A is a smoothed curve drawn to represent the average experimental alveolar oxygen pressure (ApO_2) at different altitudes shown by a large ⊙ circle for averages containing 45 or more and by a small ° circle for averages of a smaller number of observations.

Curve C

Curve C is also a smoothed curve drawn to represent the average experimental alveolar CO_2 pressures ($ApCO_2$) shown similarly by large and small circles.

Curve E

Curve E is likewise a similar smoothed curve drawn to represent the corresponding average experimental alveolar pressure ratio (APR).

Curves B, D and F

Curves B, D and F are straight lines drawn in to indicate what the hypothetical pO_2, pCO_2 and APR values would be if the body in no way compensated for the anoxia produced by a slowly increasing altitude. These curves are valuable as indicating the degree of oxygen deficiency that must be compensated for by addition of oxygen.

The curves and the individual experimental points are algebraically related as follows:

$$APR = \frac{AfCO_2\ (P_B\text{-}47)}{IfO_2\ (P_B\text{-}47) - AfO_2\ (P_B\text{-}47)} \text{ or } APR = \frac{ApCO_2}{IpO_2 - ApO_2} \text{ and}$$

$$ApO_2 = IfO_2\ (P_B\text{-}47) - \frac{AfCO_2\ (P_B\text{-}47}{APR} \text{ or } ApO_2 = 0.2094\ (P_B\text{-}47) - \frac{pCO_2}{APR}$$

where P_B indicates barometric pressure, p indicates partial pressure of gas, f indicates volumetric fraction of dry gas, A indicates alveolar air, I indicates inspired air, 47 is the vapor pressure water at 37° C., and 0.2094 is the fraction of O_2 to be inserted if pure dry air is inspired.

The alveolar pressure ratio (APR) is the alveolar CO_2 pressure divided by the difference between the oxygen pressure in the inspired air (ambient pressure 37°C. Sat.) and the alveolar oxygen pressure.

The respiratory quotient (RQ), in the sense of the combustion quotient, is the relation of the volume of CO_2 given off to the volume of O_2 absorbed obtained by analysis of the total expired gas collected over a period of time during which the subject is in a steady state (and calculated by allowing both for any change in volume of the expired air from the inspired air that may have occurred and for the amount of CO_2 present in the inspired air). Sometimes the term "respiratory quotient" has been used (either deliberately or unconsciously) to represent what might be called a "ventilation quotient", that is, the relationship obtained by analysis of total expired gas collected from a subject over a period in which he is in an unsteady state.

In the table on the chart, also reproduced in Table I, are the average values for the various altitudes of the 1025 observations by the Haldane-Priestley alveolar air method while at rest. The averages in which more than 45 observations were made are indicated in the plots by the large circle and the averages containing less than 45 observations are indicated by the small circle. The standard deviation was calculated for those averages that contain more than 45 observations. (The pCO_2 for females is usually 3 or 4 mm. less than the pCO_2 for males but there is no corresponding significant difference in the pO_2 for males and females.)

TABLE I

Alveolar O_2 and CO_2 Pressures and Alveolar Ratios at Various Altitudes While Breathing Air
Subjects Acclimatized to a Ground Altitude of 1,000 Feet

Averages: Haldane-Priestley Method at Rest

⊙ 45 observations or more

° 37 observations or less

Elevation in feet	Number of Observations	Alveolar CO_2 Mean mm.	Alveolar CO_2 Standard Deviation	Alveolar O_2 Mean mm.	Alveolar O_2 Standard Deviation	Alveolar Ratio Mean
1,000 Ground	186	36.7	2.7	102.3	5.5	0.889
2,000	8	38.1		95.5		0.892
3,000	45	36.2	2.9	89.2	5.2	0.830
4,000	8	38.5		84.8		0.902
5,000	62	36.5	2.8	81.6	4.5	0.892
6,000	54	36.2	3.1	74.2	5.2	0.832
7,000	3	40.0		67.0		0.871
8,000	10	37.4		64.8		0.860
9,000	50	35.4	3.2	61.2	5.5	0.829
10,000	92	35.8	2.6	60.9	4.6	0.923
11,000	12	36.8		53.3		0.872
12,000	61	34.8	3.2	50.7	5.4	0.857
13,000	15	36.5		44.9		0.857
14,000	26	35.4		44.0		0.894
15,000	145	32.9	2.8	44.2	5.1	0.919
16,000	9	33.8		38.8		0.899
17,000	37	30.7		38.1		0.882
18,000	55	31.8	2.5	37.9	3.8	1.006
19,000	11	29.4		36.5		0.983
20,000	81	29.4	2.6	35.3	4.6	1.054
21,000	5	24.8		30.0		0.818
22,000	45	28.1	2.7	30.2	2.9	1.033
23,000	1	29.0		30.0		1.189
24,000	2	25.0		32.0		1.269
25,000	2	23.5		32.5		1.407

Individual Observations

Total number = 1313

Sign	Number	Method	Condition
•	1025	Haldane-Priestley	Rest
ø	22	Haldane-Priestley	Rest (Work Series)
x	65	Haldane-Priestley	Work
o	106	Bag-Rebreathing	Rest
ø	40	Bag-Rebreathing	Rest (Work Series)
✳	55	Bag-Rebreathing	Work

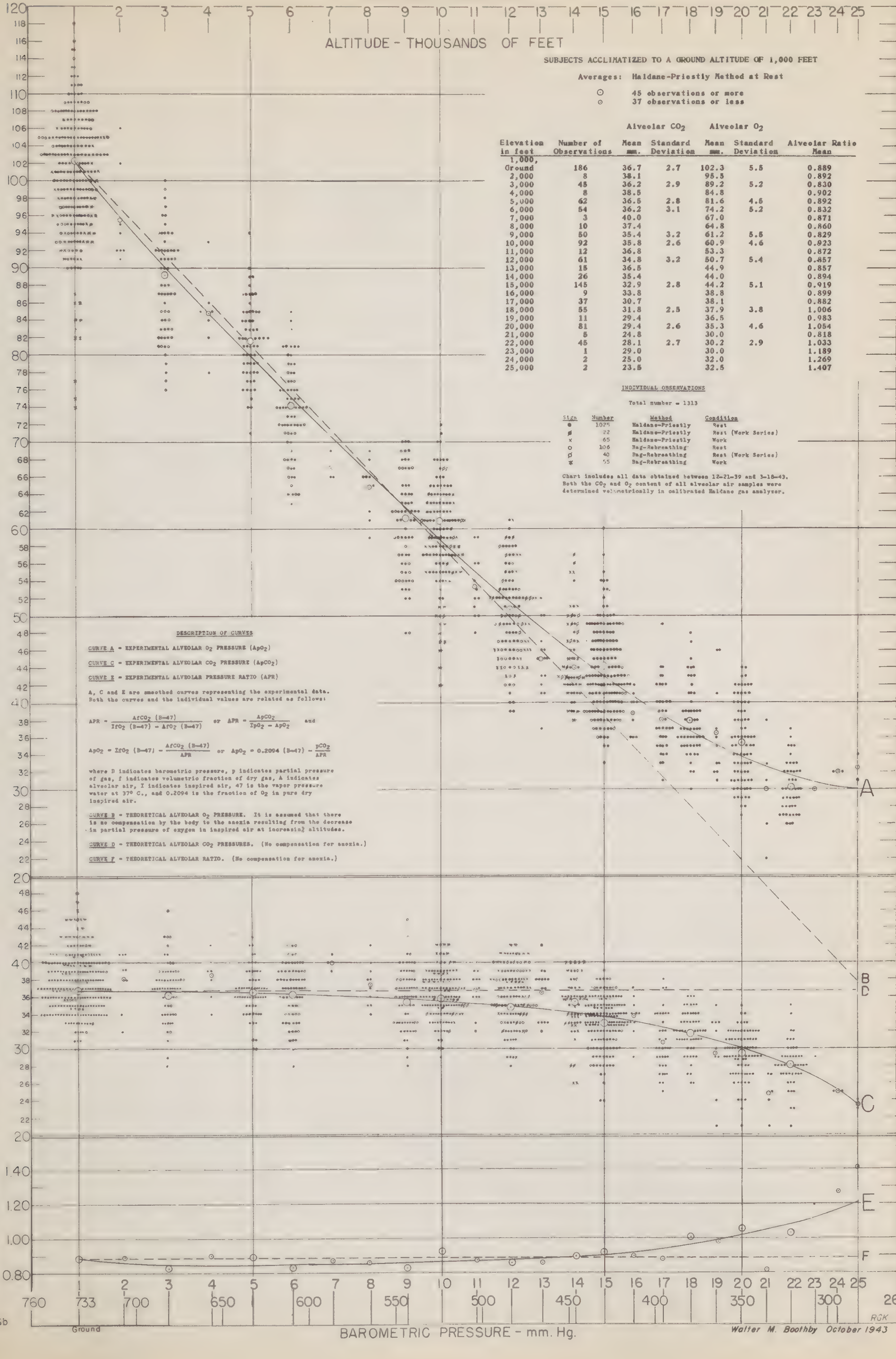
Chart includes all data obtained between 12-21-39 and 3-18-43.

Both the CO_2 and O_2 content of all alveolar air samples were determined volumetrically in calibrated Haldane gas analyzer.

W. M. B.

ALVEOLAR O_2 and CO_2 PRESSURES and ALVEOLAR RATIOS at VARIOUS ALTITUDES WHILE BREATHING AIR

MAYO AERO MEDICAL UNIT



SUBJECTS ACCLIMATIZED TO A GROUND ALTITUDE OF 1,000 FEET

Averages: Haldane-Priestly Method at Rest

⊙ 45 observations or more
⊙ 37 observations or less

		Alveolar CO_2		Alveolar O_2		
Elevation in feet	Number of Observations	Mean mm.	Standard Deviation	Mean mm.	Standard Deviation	Alveolar Ratio Mean
1,000, Ground	186	36.7	2.7	102.3	5.5	0.889
2,000	8	38.1		95.5		0.892
3,000	45	36.2	2.9	89.2	5.2	0.830
4,000	8	38.5		84.8		0.902
5,000	62	36.5	2.8	81.6	4.5	0.892
6,000	54	36.2	3.1	74.2	5.2	0.832
7,000	3	40.0		67.0		0.871
8,000	10	37.4		64.8		0.860
9,000	50	35.4	3.2	61.2	5.5	0.829
10,000	92	35.8	2.6	60.9	4.6	0.923
11,000	12	36.8		53.3		0.872
12,000	61	34.8	3.2	50.7	5.4	0.857
13,000	15	36.5		44.9		0.857
14,000	26	35.4		44.0		0.894
15,000	145	32.9	2.8	44.2	5.1	0.919
16,000	9	33.8		38.8		0.899
17,000	37	30.7		38.1		0.882
18,000	55	31.8	2.5	37.9	3.8	1.006
19,000	11	29.4		36.5		0.983
20,000	81	29.4	2.6	35.3	4.6	1.054
21,000	5	24.8		30.0		0.818
22,000	45	28.1	2.7	30.2	2.9	1.033
23,000	1	29.0		30.0		1.189
24,000	2	25.0		32.0		1.269
25,000	2	23.5		32.5		1.407

INDIVIDUAL OBSERVATIONS

Total number = 1313

Sign	Number	Method	Condition
●	1025	Haldane-Priestly	Rest
ø	22	Haldane-Priestly	Rest (Work Series)
×	65	Haldane-Priestly	Work
○	106	Bag-Rebreathing	Rest
ø	40	Bag-Rebreathing	Rest (Work Series)
✱	55	Bag-Rebreathing	Work

Chart includes all data obtained between 12-21-39 and 3-18-43. Both the CO_2 and O_2 content of all alveolar air samples were determined volumetrically in calibrated Haldane gas analyzer.

DESCRIPTION OF CURVES

CURVE A - EXPERIMENTAL ALVEOLAR O_2 PRESSURE (ApO_2)

CURVE C - EXPERIMENTAL ALVEOLAR CO_2 PRESSURE ($ApCO_2$)

CURVE E - EXPERIMENTAL ALVEOLAR PRESSURE RATIO (APR)

A, C and E are smoothed curves representing the experimental data. Both the curves and the individual values are related as follows:

$$APR = \frac{AfCO_2\,(B-47)}{IfO_2\,(B-47) - AfO_2\,(B-47)} \quad \text{or} \quad APR = \frac{ApCO_2}{IpO_2 - ApO_2} \quad \text{and}$$

$$ApO_2 = IfO_2\,(B-47) - \frac{AfCO_2\,(B-47)}{APR} \quad \text{or} \quad ApO_2 = 0.2094\,(B-47) - \frac{pCO_2}{APR}$$

where B indicates barometric pressure, p indicates partial pressure of gas, f indicates volumetric fraction of dry gas, A indicates alveolar air, I indicates inspired air, 47 is the vapor pressure water at 37° C., and 0.2094 is the fraction of O_2 in pure dry inspired air.

CURVE B - THEORETICAL ALVEOLAR O_2 PRESSURE. It is assumed that there is no compensation by the body to the anoxia resulting from the decrease in partial pressure of oxygen in inspired air at increasing altitudes.

CURVE D - THEORETICAL ALVEOLAR CO_2 PRESSURES. (No compensation for anoxia.)

CURVE F - THEORETICAL ALVEOLAR RATIO. (No compensation for anoxia.)

I - 6b

RGK

Walter M. Boothby October 1943

EQUIVALENT ALTITUDES BREATHING GAS MIXTURES

CHART A-2

November, 1943

Equivalent Altitudes Breathing Gas Mixtures

Chart A-2

This chart shows the relation between physiologically equivalent altitudes for persons breathing gas mixtures containing various concentrations of oxygen. Equivalent altitudes are defined in terms of identity of alveolar gas composition. Thus altitude A breathing gas mixture X is equivalent to altitude B breathing gas mixture Y when the composition of alveolar gas is identical in the two cases. Equivalent altitudes calculated in this way would be expected to correspond with equivalent altitudes defined in terms of equal arterial oxygen saturations. Comparison of Chart A-2 with Chart B-4 shows that this is indeed the case.

Construction of Chart:

Each curve on the chart was constructed by calculating for a given gas mixture the altitudes physiologically equivalent to various altitudes breathing air. The equation defining this relation is given in Section IV (Equation 15) of the Essay on the Composition of Respiratory Gases. It may be written in the form

$$P_B = \frac{.209}{F_{O_2}} \left\{ P_B{}^* - 47 - pCO_2{}^* \frac{(1 - R.Q.)}{R.Q.} \times \frac{(F_{O_2} - .209)}{.209} \right\} + 47$$

where the quantities marked with an asterisk denote values breathing air.

1. *The Value of R. Q.*—The value of R. Q. used for the calculation was 0.85.

2. *The Value of Alveolar pCO_2*—To make the calculations it is necessary to adopt a nominal value for alveolar pCO_2 at each altitude while breathing air. The exact value chosen is not critical owing to the fact that we are equating two altitudes under conditions in which the alveolar carbon dioxide pressures are by definition the same. The actual values used are shown in Table I below; they were obtained from the smoothed data of Boothby (Chart A-1) and of Lutz & Schneider.

TABLE I

Altitude (Thousand feet)	0	5	10	12	14	16	18	20	22	24
Alveolar pCO_2 mm. Hg	40	38	36	35	34	33	32	30	28	25

The small effect of large variations of CO_2 on the calculation of equivalent altitudes is illustrated in the following example:

What altitude breathing 100% oxygen is equivalent to breathing air at 16000 ft. ($P_B = 412$ mm. Hg)?

a) Let $pCO_2{}^*$ on air = 33 mm. as assumed for chart.

$$P_B = \frac{.209}{1.0} \left\{ 412 - 47 - 33 \frac{(1 - .85)}{.85} \quad \frac{(1.0 - .209)}{.209} \right\} + 47 = 117 \text{ mm. Hg or } 43870 \text{ feet}$$

b) Let $pCO_2{}^*$ on air = 28 mm.

$$P_B = .209 \left\{ 412 - 47 - 28 \frac{(1 - .85)}{.85} \quad \frac{(1.0 - .209)}{.209} \right\} + 47 = 118 \text{ mm. Hg or } 43690 \text{ ft.}$$

Thus a change of 5 mm. pCO_2 produces a change of only 180 feet in the calculated equivalent altitude.

Limitations:

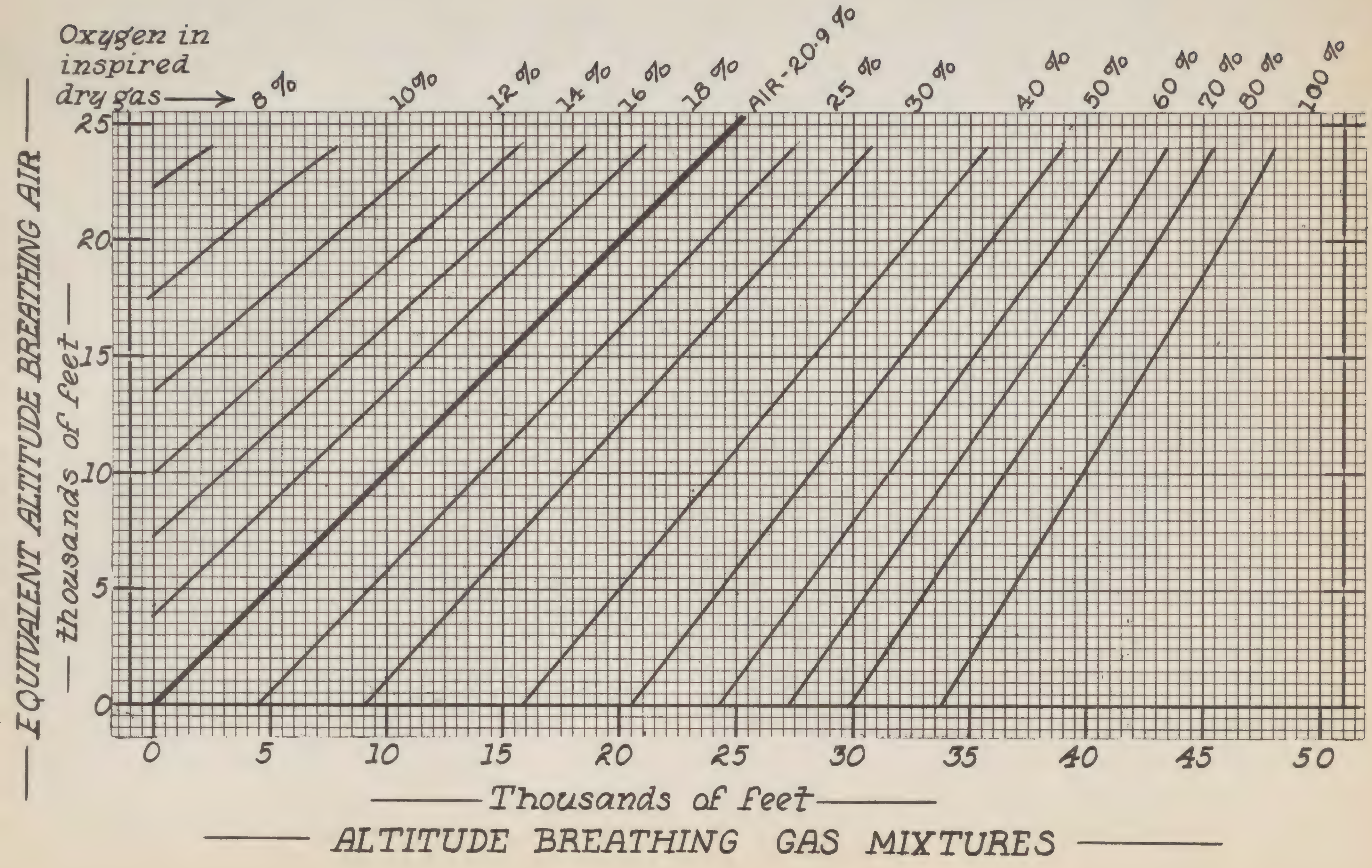
The values shown in Chart A-2 are valid only under the defined conditions of equality of alveolar gas composition. If, as a result of fear, pain or other factors, an individual hyperventilates in such a way that the alveolar pCO_2 varies independently of the alveolar pO_2, then the values shown in the Chart do not apply.

Sources: 1) Boothby, W. M. Chart A-1

2) Lutz and Schneider, Am. J. Physiol. *50*, 280, (1919)

J. R. P. and F. B., Jr.

EQUIVALENT ALTITUDES



COMPARISON OF STANDARDS FOR CALCULATING
OXYGEN REQUIREMENTS
(5000 FT. EQUIVALENT)

CHART A-3

Comparison of Standards for Calculating Oxygen Requirements
(5000 ft. Equivalent)

Chart A-3

Purpose of Chart: To compare the results of two methods commonly employed to specify the fractions of oxygen in dry inspired gas at altitude which are required to simulate a given altitude breathing air.

Explanation: Curve I is based on the equivalence of Po_2 in inspired air saturated with water vapor at 37° C. It is defined by the approximation formula given in Essay A, Section V, Equation 21

$$F_{O_2}^{5000} = \frac{122.6}{P_B - 47}$$

Curve II is based on the equivalence of pO_2 and pCO_2 in alveolar air. It is defined by the approximation formula given in Essay A, Section V, Equation 19

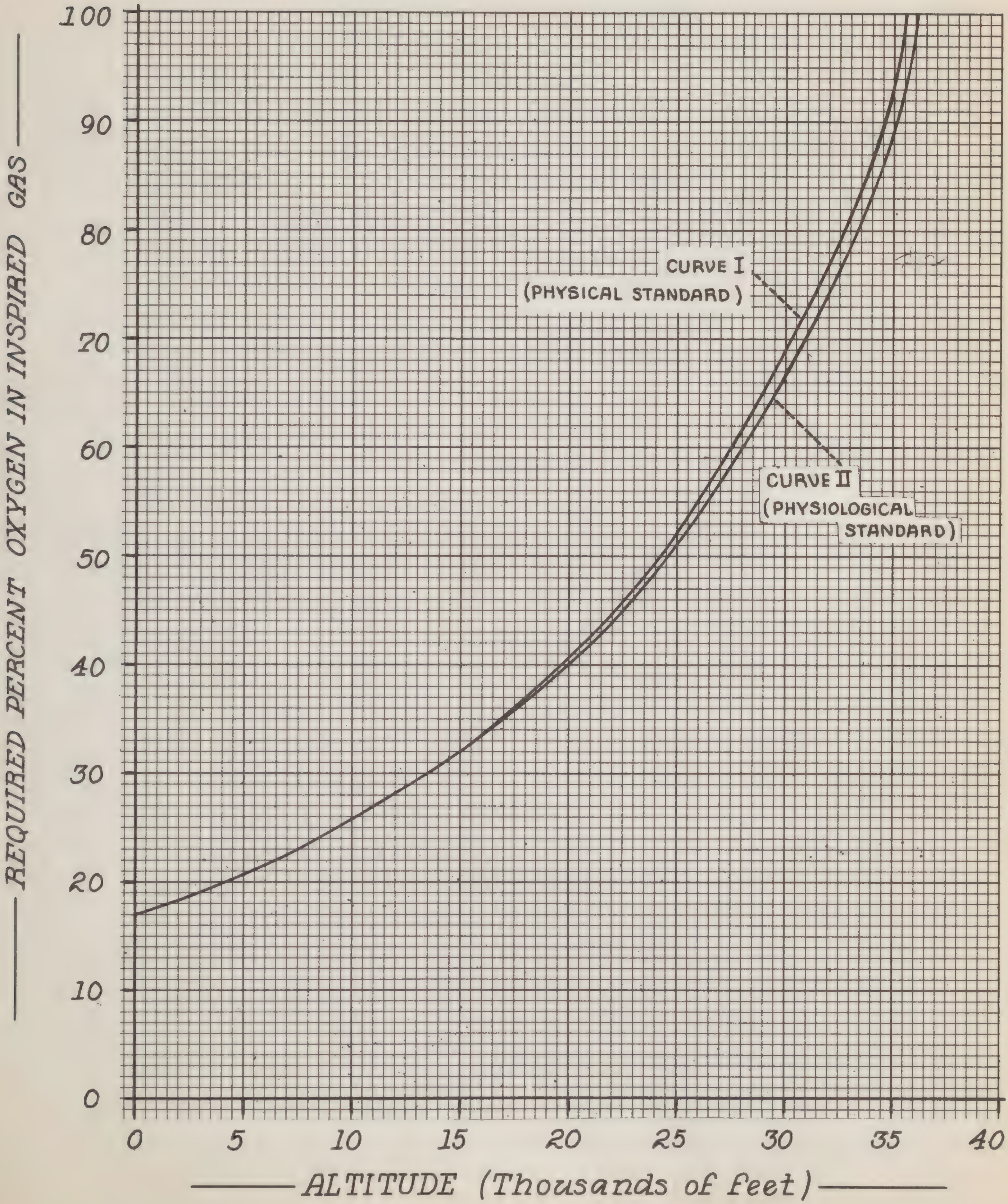
$$F_{O_2}^{5000} = \frac{124}{P_B - 40}$$

The maximum difference between the two methods of specifying oxygen requirements at altitude is less than 5%. This difference is considerably less than variations in composition of gas delivered by present-day dilutor-demand regulators.

Limitations: Curve I is based on physical standards which are unaffected by physiological variables. It specifies a slightly greater fraction of oxygen at each altitude than does Curve II which is based on equivalence involving physiological variables as discussed above. Curve I is suitable for defining specifications for oxygen equipment; it is the basis of the Fo_2 values presented in Table P-2. The method of calculation employed in constructing Curve II should be considered in connection with quantitative physiological research work at altitude.

F. B., Jr.

COMPARISON OF STANDARDS FOR CALCULATING OXYGEN REQUIREMENTS
(5,000 ft. equivalent)



THE COMPOSITION OF INSPIRED GAS REQUIRED TO MAINTAIN A CONSTANT ALVEOLAR pO_2

CHART A-4

August, 1943

The Composition of Inspired Gas Required to Maintain a Constant Alveolar pO_2

Chart A-4

Use of Chart: Determination of oxygen requirements at altitude.

In order to calculate the fraction of oxygen in inspired air required to maintain a constant alveolar gas tension at altitude it is necessary to know the metabolic R. Q. and the alveolar pCO_2. The equation is

$$Fo_2 = \frac{pO_2 + pCO_2}{P_B - 47 - pCO_2 + \dfrac{pCO_2}{R.Q.}}$$

(Equation 10, p. 5, Essay A)

1. *The Value of Alveolar Pressure of Carbon Dioxide.*

In the absence of anoxia, respiration is adjusted to maintain a relatively constant CO_2 pressure in the lung gases and arterial blood. The nominal value of this pressure for healthy young men is 40 mm. of Hg. One recent set of data obtained by alveolar gas analysis on 16 young men gave an average pCO_2 of 40.5 mm. of Hg. Another set obtained in another laboratory by arterial blood analysis gave 39.6 mm. of Hg. Examination of these data indicates that all the pCO_2 values for these subjects were between 35 and 45 mm. of Hg. These values, therefore, were used as the limits to employ in estimating the changes in composition of inspired gas required to maintain a constant alveolar oxygen tension when the barometric pressure is changed. The shaded areas in the chart represent the spread in Fo_2 values due to this range of alveolar carbon dioxide pressures found in tested subjects. These values are assumed to apply except when the respiration is altered by anoxic drive. This does not occur significantly in young men in the range of alveolar oxygen tensions covered in this chart.

2. *The Value of R. Q.*

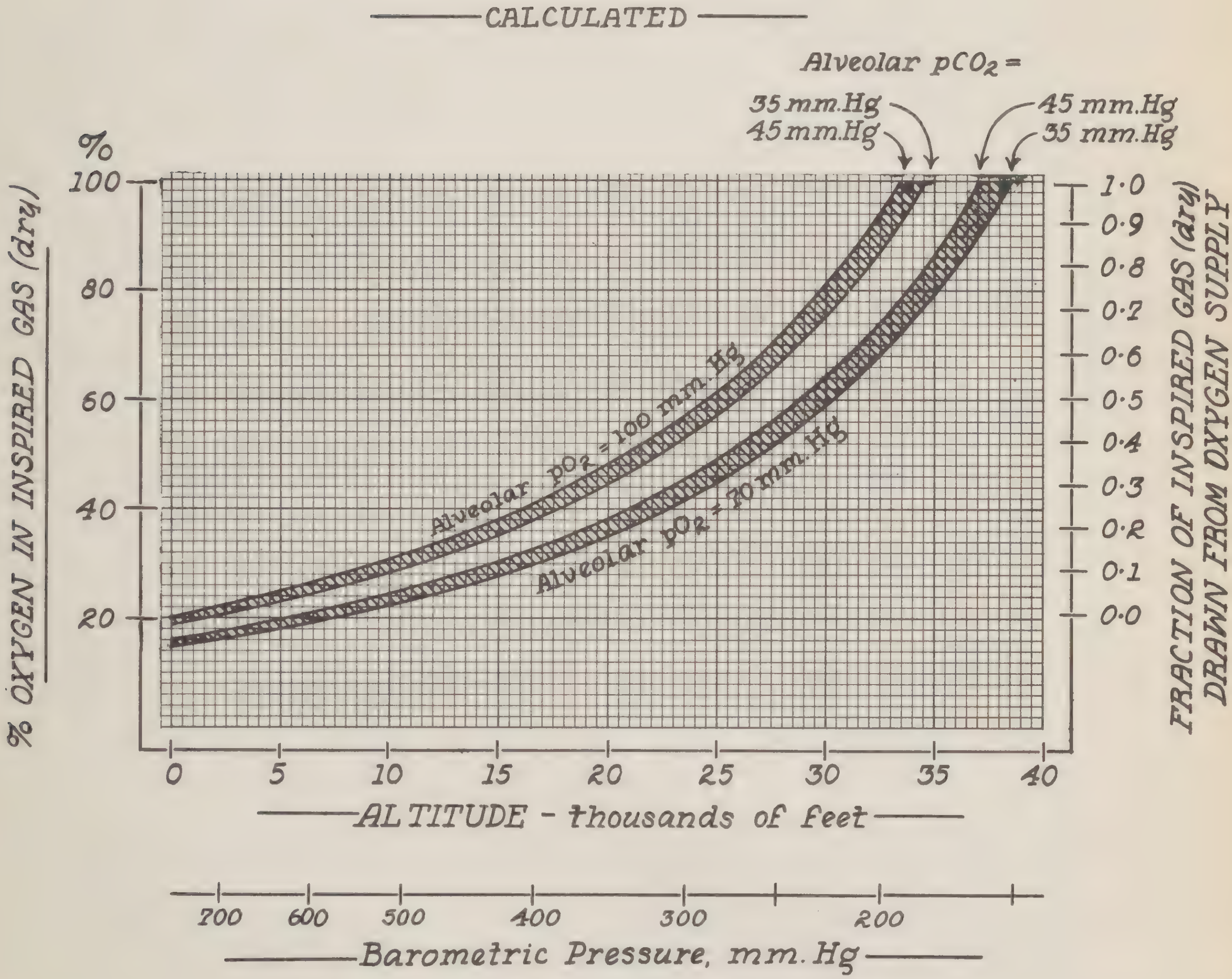
In the steady state of respiratory exchange the R. Q. in equation (10) is the metabolic respiratory quotient (R. Q.). All values are therefore confined between 0.7 and 1.0. For most people during most of the day this value is 0.82. The effect of R. Q. on the calculation of Fo_2 is small enough to be neglected in specifications for oxygen regulators since inspired gas mixtures provided by aviation oxygen equipment are not adjusted to better than 0.01. The values of Fo_2 given in Chart A-4 may therefore be assumed applicable for all values of R. Q. between 0.8 and 1.0.

There are two important conditions which may cause a prolonged deviation from a steady state: first, hyperventilation due to anoxia and, second, that due to excitement. With adequate oxygen equipment most flying can be done without anoxia. Thus deviations from the above predictions will affect only the small number of men who must go to extreme altitudes for short times. A prolonged condition of anoxia, over 40 minutes, will lead to a new steady state of respiratory exchange and the above equations are again valid. Although the pCO_2 will now be lower than usual this merely means that the pO_2 is higher, i. e. the deviation from prediction is in a safe direction. The same conclusion applies to hyperventilation due to emotional stimuli. The expected deviations from predicted steady state conditions, therefore, are not in a dangerous direction insofar as alveolar oxygen pressure is concerned.

The scale on the right hand side of Chart A-4 was calculated as in Table P-4, Section IV. From the respiratory minute volume it is possible to estimate, using this scale, the fraction of oxygen taken from the supply per minute at any altitude when the regulator is designed to maintain one of the indicated alveolar oxygen tensions. Thus problems of economy and of design requirements for oxygen regulators can be solved by using this chart.

F. B., Jr.

OXYGEN REQUIRED TO MAINTAIN STATED ALVEOLAR OXYGEN PRESSURES AT ALTITUDE



OXYGEN-NITROGEN MIXTURES REQUIRED TO SIMULATE ALTITUDES

CHART A-5

November, 1943

Oxygen-Nitrogen Mixtures Required to Simulate Altitudes

Chart A-5

Use of Chart: Experiments in which altitudes are to be simulated by breathing oxygen-nitrogen mixtures at sea-level.

Explanation: The curve is calculated from Equation 15, Section IV in Essay A

$$P_B = \frac{.209}{F_{O_2}} P_B^* + \frac{(F_{O_2} - .209)}{F_{O_2}} \times 47 - pCO_2 \frac{(F_{O_2} - .209)}{F_{O_2}} \frac{(1 - RQ)}{RQ}$$

At sea-level, $P_B = 760$ mm. Hg. Let R. Q. = 0.85. Substituting these values in (15) and solving for F_{O_2} we have—

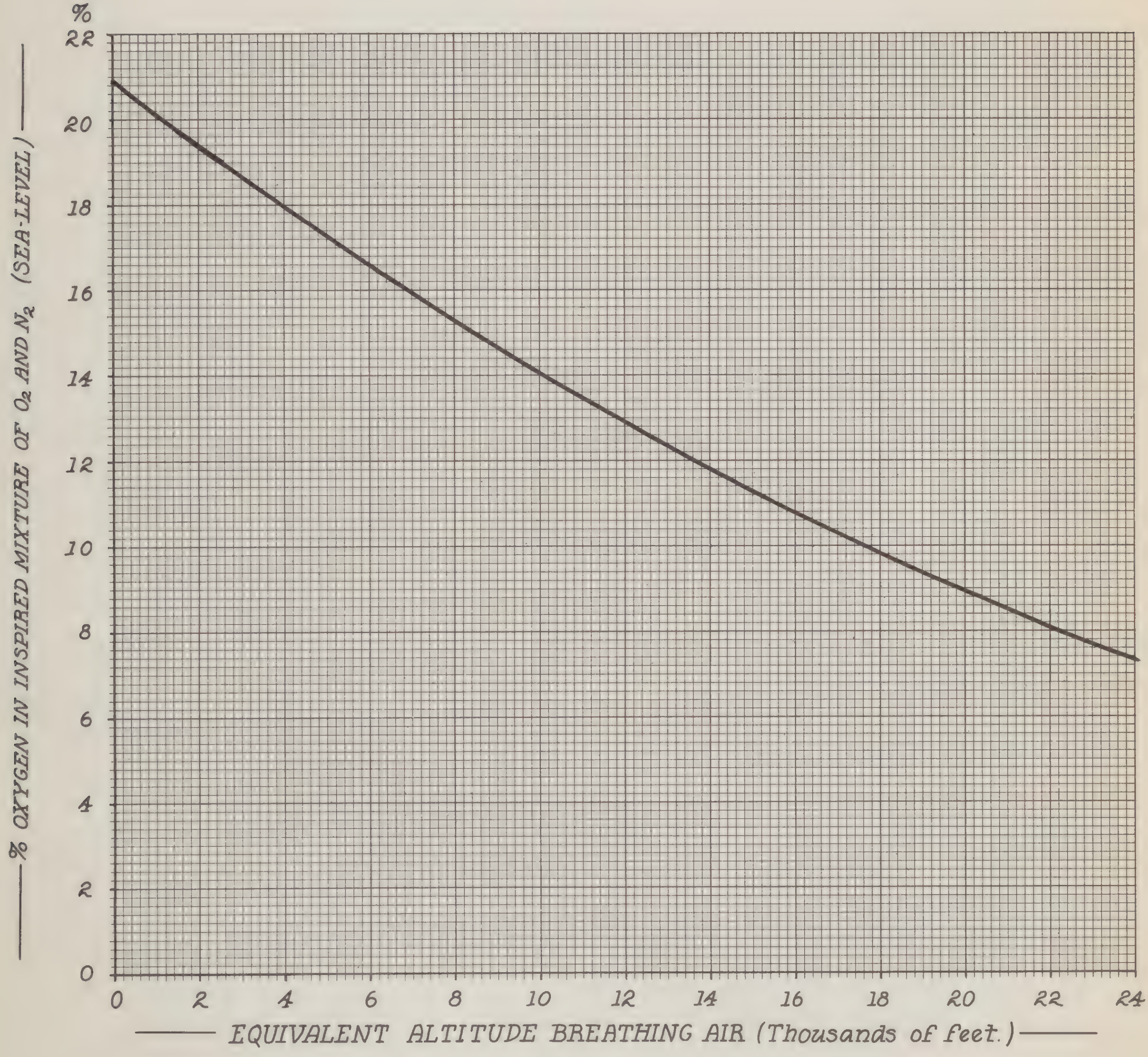
$$F_{O_2} = \frac{.209\ (P_B^* - 47 + .177\ pCO_2)}{(713 + .177\ pCO_2)}$$

The pCO_2 corresponding to each P_B^* is defined in Table I, Chart A-2. However, the values of R. Q. and pCO_2 chosen for the calculation are not critical. Within the range of equivalent altitudes shown in the chart the F_{O_2} values do not differ by more than 0.1% O_2 from similar values calculated on the basis of equal P_{O_2} in inspired air saturated at 37° C. (cf. also Chart A-3).

Limitations: It should be emphasized that the chart applies only to steady state conditions. Evidence obtained from the rate of fall of arterial oxygen saturation while breathing gas mixtures indicates that 5-15 minutes are required to bring the oxygen saturation to a steady level (cf. also Essay A, Section VI "Non-Steady State").

F. B., Jr. and J. R. P.

GAS MIXTURES REQUIRED TO SIMULATE ALTITUDES



SECTION R

Respiratory and Metabolic Data

COMPONENTS OF RESPIRATORY MINUTE VOLUME

CHART R-1

November, 1943

Components of Respiratory Minute Volume

Chart R-1

Use of Chart:

1) Definition of components of respiratory minute volume.
2) Calculation of consumption of dry gas at O° C., 760 mm. Hg corresponding to any given respiratory minute volume.
3) Calculation of respiratory minute volume from measurement of consumption of dry gas at O° C., 760 mm. Hg.

Explanation:

The respiratory minute volume is defined as the sum of the increases (or decreases†) of lung volume which take place in one minute by successive inspiratory (or expiratory†) movements. It is equal to the volume of inspired (or expired†) air measured at body temperature, 37° C., ambient pressure and saturated with water vapor (abbreviated throughout these charts as BTPS). At sea-level the corrections for water vapor and temperature are relatively small and are frequently omitted in presenting respiratory data. At altitude, however, the water vapor and temperature corrections become increasingly important and large errors are introduced if the respiratory minute volume is considered equal to the volume of gas inspired from or collected in a spirometer at ambient temperature and pressure. The chart is intended to show the sources from which the different components of lung volume increase are derived and the relative fraction of each as a function of altitude. The fractions are independent of the absolute value of the respiratory minute volume and apply equally well to the gas components of a single inspiration.

Example of Use:

Consider an altitude of 32,600 feet ($P_B = 200$ mm. Hg). The chart shows that at this altitude only a small fraction (0.18) of the total respiratory minute volume is derived from dry gas measured at O° C., 760 mm. Hg. Isothermal expansion of this gas to ambient pressure brings the volume to 0.67 of the total and further isobaric expansion to body temperature increases the value to 0.77 of the total. The remaining fraction (0.23) is contributed by saturation of the dry gas with water vapor in the respiratory passages. *Conversely,* if the consumption of dry gas (O° C., 760 mm. Hg) is L liters per minute then at 32,600 feet the respiratory minute volume is L/0.18 liters per minute BTPS.

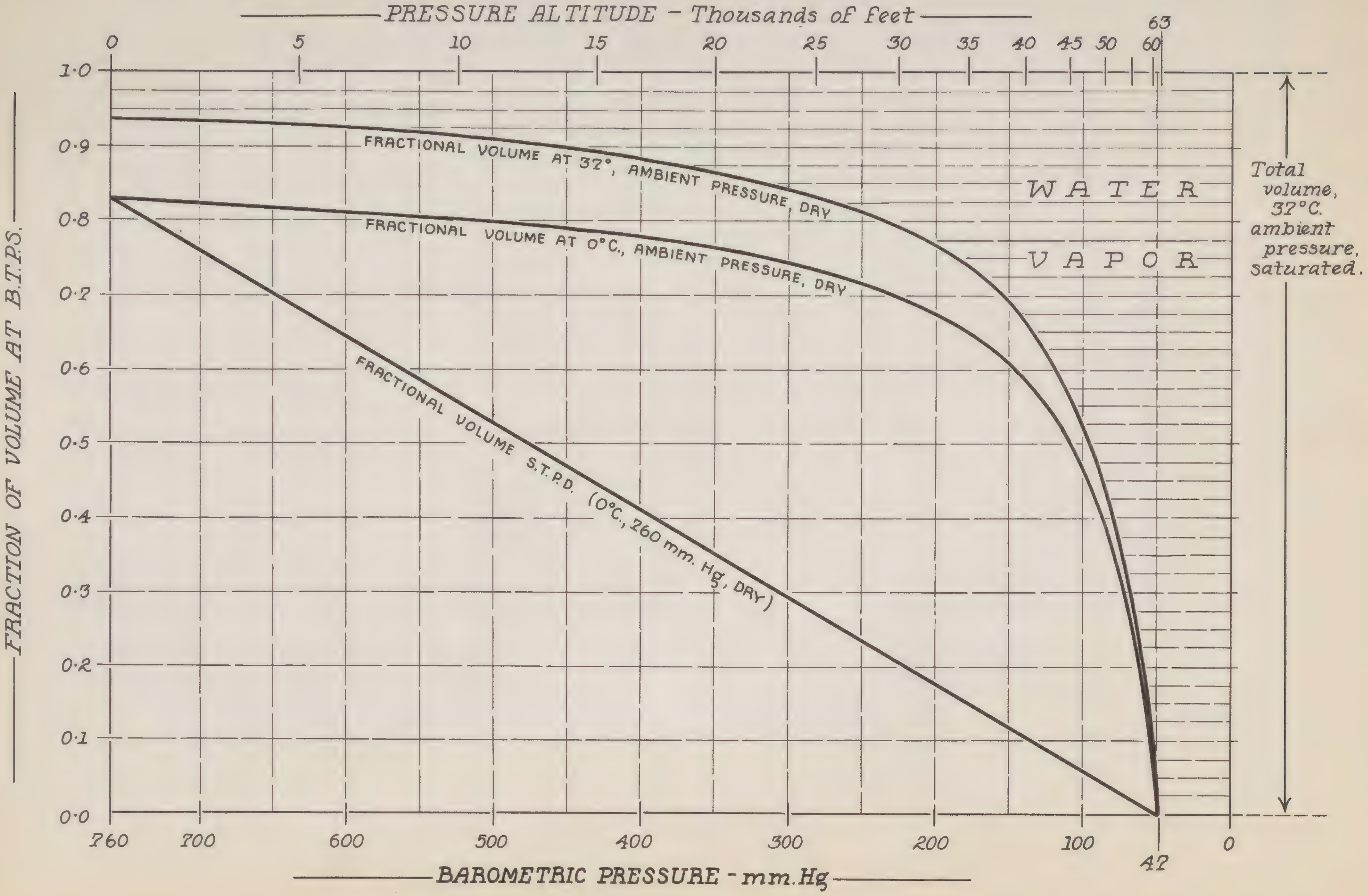
Equations used for calculating chart:

$$\text{Upper (heavy) curve} = \frac{P_B - 47}{P_B}, \qquad \text{Middle curve} = \frac{273}{310} \times \frac{(P_B - 47)}{P_B}, \qquad \text{Lower curve} = \frac{273}{310} \times \frac{(P_B - 47)}{760}$$

† The inspiratory minute volume (BTPS) is not exactly equal to the expiratory minute volume (BTPS) owing to the fact that less CO_2 is produced than O_2 consumed. This difference may amount to 0.15 liters/min. thereby introducing a discrepancy of 1.5% when the respiratory minute volume is 10 liters/min.

H. F. H., Jr.

COMPONENTS OF RESPIRATORY MINUTE VOLUME (B.T.P.S.)



RESPIRATORY REQUIREMENTS DURING EXERCISE

CHART R-2

November, 1943

Respiratory Requirements During Exercise

Chart R-2

Explanation:

The data include 224 observations on 123 individuals. No classification according to age, height and weight has been made although the majority of subjects were less than 30 years old. The measurements were made several minutes after the beginning of exercise when "steady state" conditions were attained. Observations at altitude were made under conditions in which no serious anoxia would be expected, but actual data regarding alveolar oxygen pressures or arterial saturations were not obtained.

The center line indicates average values and the boundary lines include more than 90% of the observations. Respiratory volumes have been corrected to body temperature and pressure, saturated with water vapor at 37° C. (BTPS)

Limitations:

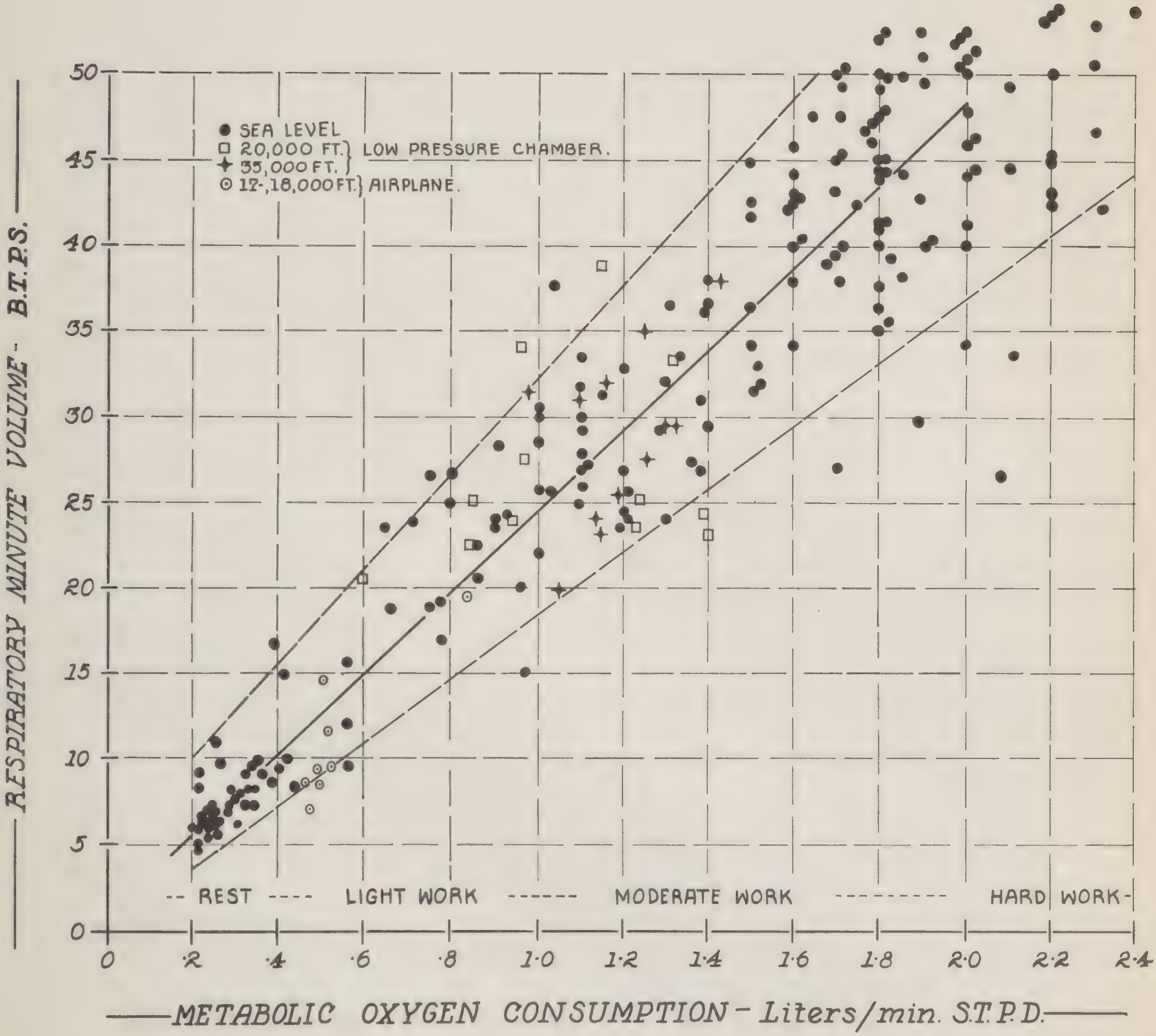
The data apply only to conditions in which the respiratory minute volume has been altered as a result of exercise uncomplicated by anoxia, CO_2 accumulation, cold or other factors. There is evidence that an increase of metabolism produced by shivering results in a greater increase of respiratory minute volume than that indicated by the chart for exercise.

Sources:

1) Harvard Fatigue Laboratory, Miscellaneous Data
2) Dill, D. B., Manuscript from Wright Field (1942)
3) Dill, D. B., et al. J. Physiol. *71,* 47 (1931)
4) Christensen, E. H. Sk. Arch. f. Physiol. *76,* 88 (1937)
5) Taylor, C., Am. J. Physiol. *135,* 27 (1941)

J. R. P.

RESPIRATORY REQUIREMENTS DURING EXERCISE



OXYGEN REQUIREMENT DURING EXERCISE

CHART R-3

November, 1943

Oxygen Requirement During Exercise

Chart R-3

Use of Chart:

1) Design of closed oxygen supply systems
2) Efficiency of different types of work

Explanation:

This chart shows the oxygen requirements associated with three forms of work load—lifting weights, climbing on a treadmill, and pedalling on a bicycle ergometer. Experimental points are shown only for the bicycle ergometer when pedalled at the rate of 70 r. p. m. The experimental scatter about the lines shown on the chart is about the same for the three types of work. The dashed part of the weight lifting curve is extrapolated. The points include observations on 11 individuals and were obtained in three laboratories. The points represent steady state conditions.

The slope of each line on the chart is the reciprocal of the efficiency. The efficiency is defined as follows:

$$\text{Efficiency} = \frac{\text{Work done (calories/min.)}}{\text{Calorimetric equivalent of increase in oxygen consumption (calories/min.)}}$$

For any given type of work the efficiency varies with the velocity of muscular movement. There is in general an optimum velocity; in the case of the bicycle ergometer this occurs at 70 r. p. m. at which velocity the efficiency averages 22% at all work loads. The efficiency falls to 15% at velocities of 20 r. p. m. or 170 r. p. m. The upper limit of efficiency for muscular work is about 25% and for most forms of exercise is of the order of 15%.

It is the opinion of experienced investigators that the subjective sensation of degree of work load depends on the metabolic oxygen consumption rather than on the actual work load. Thus a work load of 500 kg. meters/min. on the bicycle ergometer would be subjectively classified as "moderate" whereas a similar work load lifting weights would be subjectively classified as "hard" or "severe."

Sources: 1) Christensen, E. H., Sk. Arch. f. Physiol. *76*, 88 (1937)

2) Dickinson, S., J. Physiol. *67*, 242 (1929)

3) Schneider, E. C., Am. J. Physiol. *97*, 353 (1931)

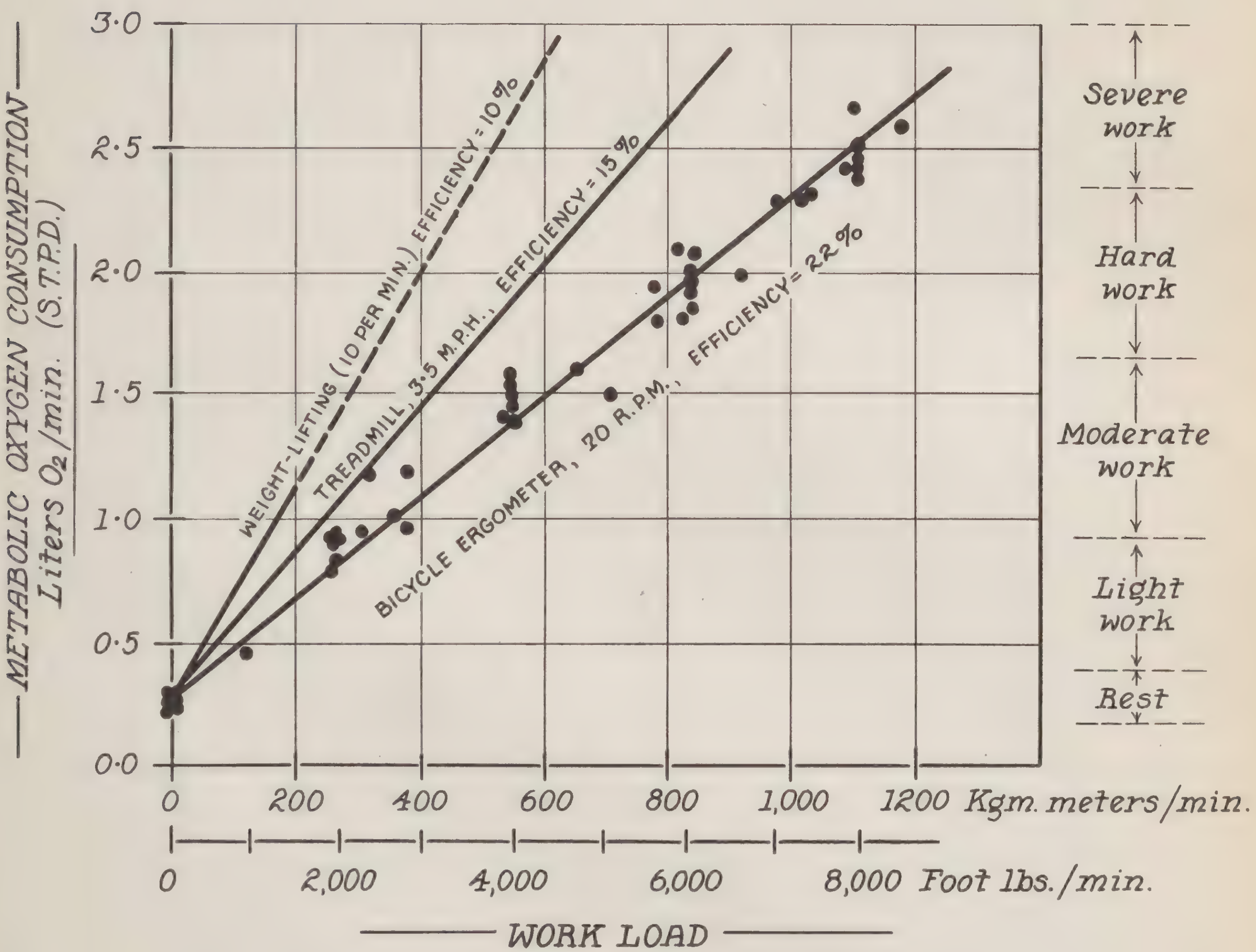
4) Taylor, C., Am. J. Physiol. *135*, 27 (1941)

5) Harvard Fatigue Laboratory, Miscellaneous data

6) Mayo Aero-Medical Unit, Miscellaneous data

J. R. P.

OXYGEN REQUIREMENTS DURING EXERCISE



RESPIRATORY RESPONSE TO CARBON DIOXIDE

CHART R-4

August, 1943

Respiratory Response to Carbon Dioxide

Chart R-4

The experiments were performed on 23 male college students ranging in age from 18 to 28 years, lying at rest (supine) and breathing through a Siebe-Gorman half mask and egg-shell valves a mixture containing 21% O_2 (balance N_2) plus 0, 1, 2, and 4% CO_2, all at sea level (Berkeley, Calif.). Each inhalation period lasted long enough for respiratory volume to become stabilized and volume of air expired into delicately balanced spirometers was measured over this period.

Assumptions used: Average curve for volume of expired air is extrapolated back to zero from the level reached while breathing 1% CO_2. Some of the increases produced by this mixture were so small (4%) as to justify the tentative conclusion that 1% CO_2 is about the weakest concentration in inspired air by which breathing is likely to be stimulated significantly under these conditions. The part of the curve between this and the zero point should be evaluated accordingly.

Limitations:

1. The results apply only to subjects lying supine at rest, breathing 21% O_2 at sea level. High concentrations (96-99%) of O_2 at sea level will markedly increase the response to each of these percentages of CO_2 (Shock & Soley). Corresponding data at higher altitudes are lacking. The effect of position alone would probably not be great.

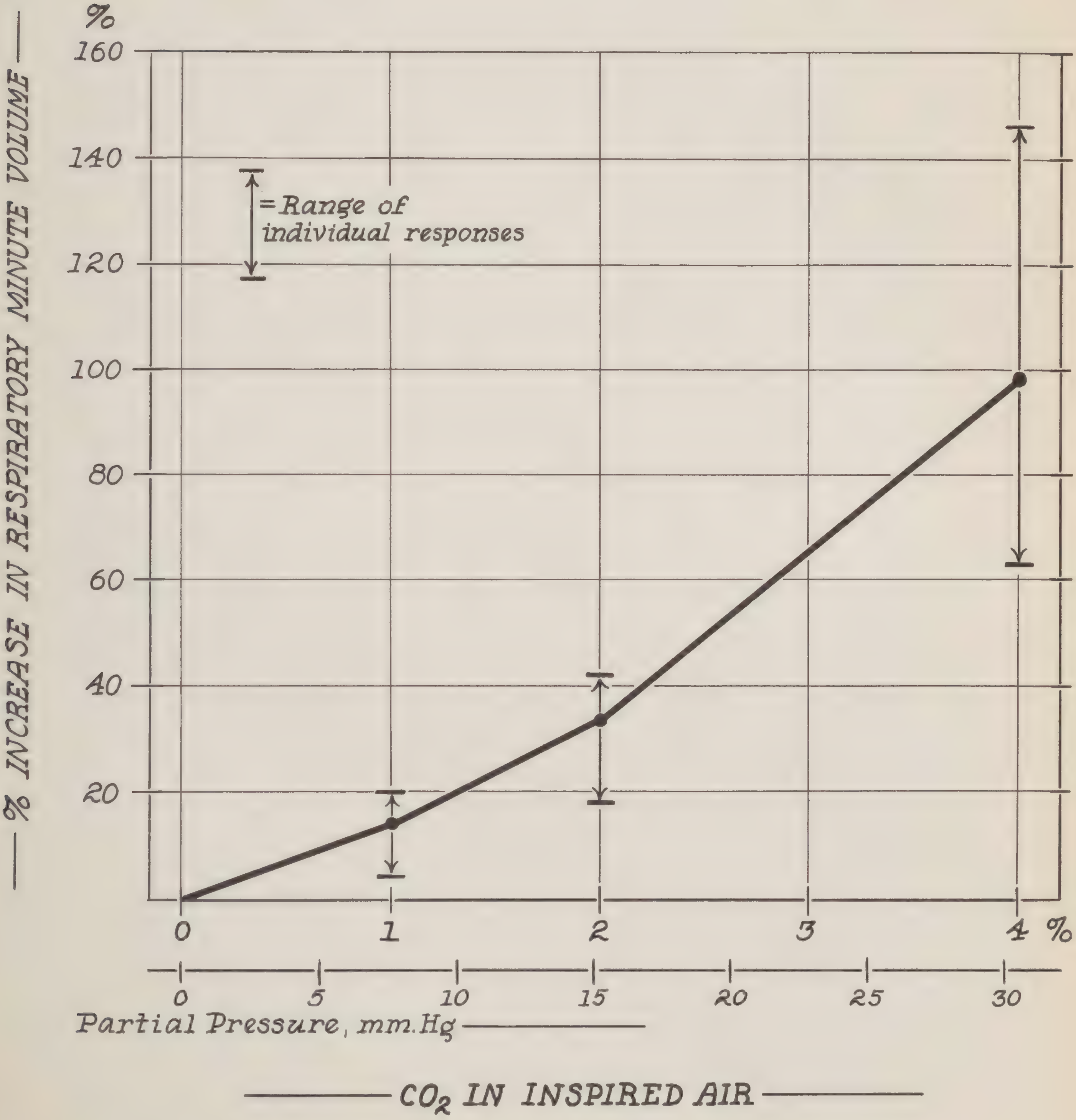
2. Subjective discomfort would probably not be produced by CO_2 until respiratory minute volume is increased by at least 50% over the control level (subjects lying supine at rest and at sea level).

3. Other factors such as exercise, anoxia, cold, and excitement would unquestionably increase the respiratory response to a given CO_2 concentration in the inspired air, but pertinent data are not available at present.

Source of Data: Shock and Soley (Am. J. Physiol. *130, 777,* 1940)

C. F. S.

RESPIRATORY RESPONSE TO CARBON DIOXIDE AT SEA LEVEL



PEAK INSPIRATORY VELOCITIES DURING EXERCISE
AT SEA-LEVEL

CHART R-5

March, 1943

Peak Inspiratory Velocities During Exercise at Sea-level

Chart R-5

Explanation:

(1) Vertical lines indicate boundaries which include the standard deviation about the mean.

(2) *Solid Circles* show the mean values from 27 subjects breathing without inspiratory resistance to flow. *Open Circles* are mean values from same subjects breathing against a constant inspiratory resistance of 1.20 mm. H_2O per liter/min.

(3) The term *constant resistance* refers to a device in which the pressure drop is proportional to the rate of flow. Charcoal canisters having this characteristic were used to provide resistance to inspiration.

(4) A resistance of 1.20 mm. H_2O per liter per minute (shown in chart) is sufficient to cause discomfort even at low flows (10 liters/min.). Lesser values of resistance yielded results which are included between the extremes shown in the chart.

(5) Respiratory minute volumes given in the chart have been recalculated from the original data to body temperature and pressure, saturated (BTPS).

Limitations:

(1.) The minute volumes were varied by exercising on a bicycle ergometer at sea-level (cf. Chart #R-3). Other stimuli to increased respiration (anoxia, cold or CO_2) may not give comparable results.

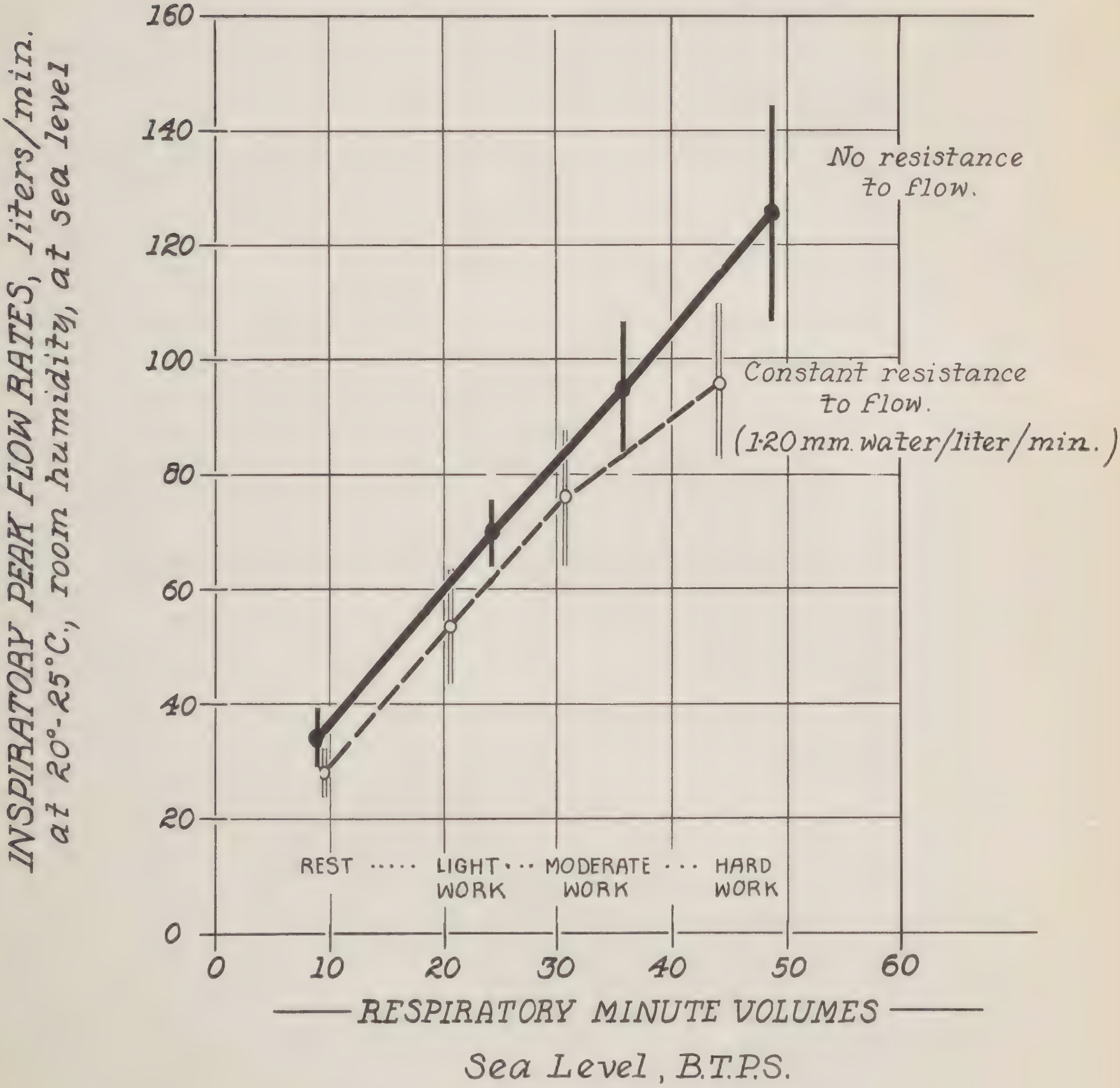
(2) The results may not be applicable to variable resistances to inspiration. Orifices or complex resistances from demand regulators are examples of this type. More data are needed in this connection.

(3) The data may be applied only to sea-level conditions. For the same respiratory minute volume (BTPS) the volume of dry inspired gas is greatly reduced at altitude (Chart #R-1) and the peak velocity may therefore be altered.

Source: Harvard Report OSRD No. 1222

J. C. L.

PEAK INSPIRATORY VELOCITIES DURING EXERCISE AT SEA LEVEL



RESISTANCE TO BREATHING

CHART R-6

November, 1943

Resistance to Breathing

Chart R-6

The data shown on the accompanying chart were obtained by plotting the mask suction pressures against the corresponding peak instantaneous rates of airflow. The instantaneous rates of airflow were determined by recording the instantaneous pressure changes during breathing in oxygen masks modified to hold various calibrated orifices. The subjects breathed both ways through these orifices, the characteristics of which were such that inspiratory and expiratory pressure fluctuations were approximately equal. The magnitude of the pressure fluctuations for a given air flow velocity was varied by changing the size and number of orifices used. The resistance to breathing was brought about by sudden reduction in orifice area by plugging one or more in the mask. The pressure fluctuations were recorded optically with a segment capsule manometer.

The records were taken on eleven subjects seated quietly, and immediately after light, moderate and heavy exercise. Light exercise consisted of sitting down and standing up once every 5 seconds for three minutes. Moderate exercise consisted of jog trotting 100 yds. Heavy exercise was a 100 yd. dash. At the conclusion of each exercise, various orifice combinations were used, and the subject was asked his opinion of the resistance of each combination.

The grades of resistance to breathing were as follows:

Resistance unnoticed—Subjects not conscious of resistance to breathing (open circles).
Resistance noticed—(closed circles and triangles).

(1) Light—resistance noticed but not uncomfortable.

(2) Moderate—resistance not uncomfortable for a short while but one which (in the opinion of the subject) would become uncomfortable after a long period.

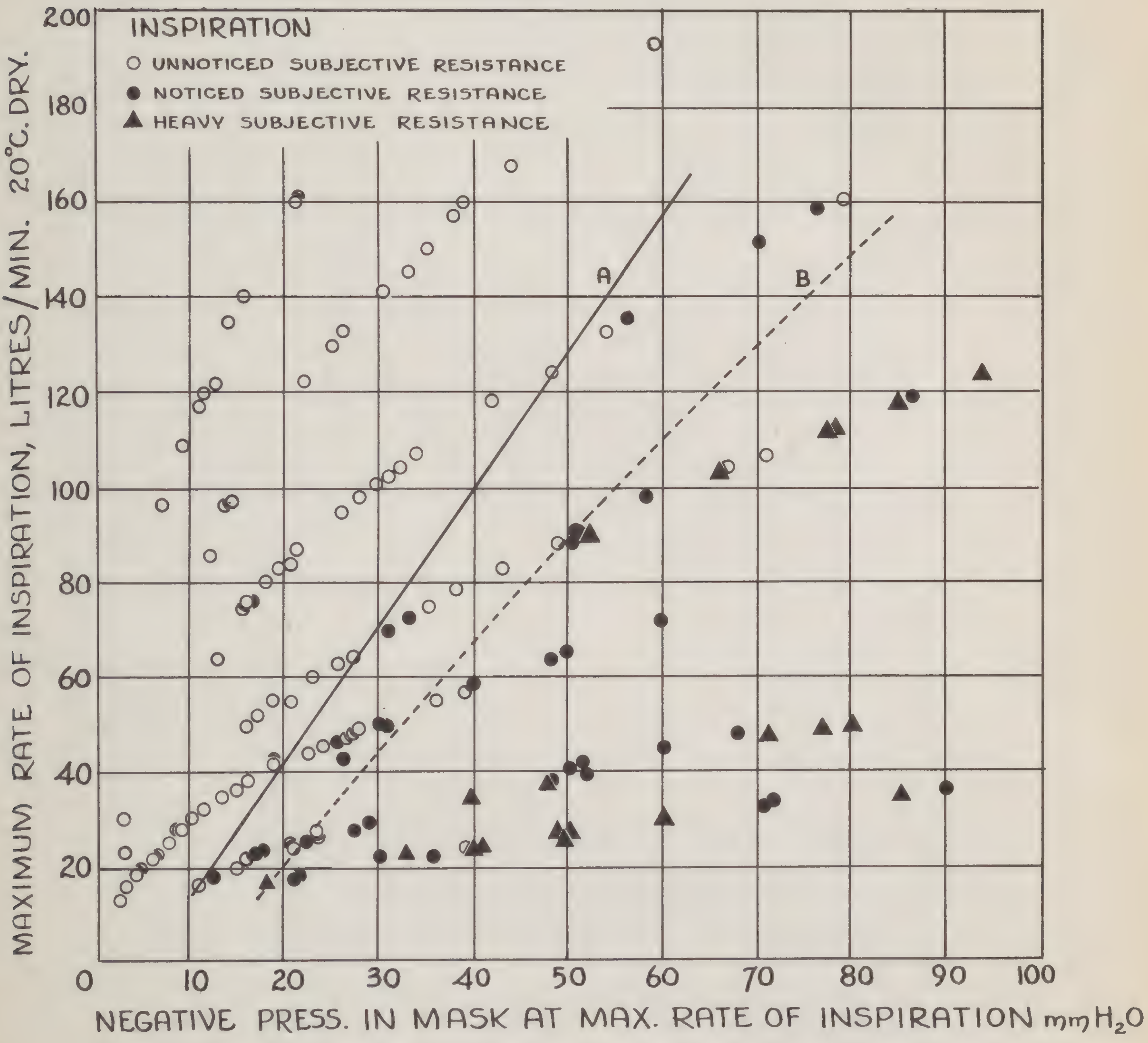
(3) Heavy (triangles)—resistance uncomfortable and too high for a short period; occasional desire to remove mask for relief.

On the chart, curve A is a line which has only unnoticed resistances to the left of it. Curve B has approximately an equal number of unnoticed and noticed resistances on either side of it, and it has no heavy resistances to the left of it.

Source: Report B-25, January, 1943. Canadian N. R. C. No. C2428

J. S. H.

RESISTANCE TO BREATHING



SECTION B

Properties of Blood

November, 1943

Oxygen Dissociation Curves for Human Blood at 37°C.

Chart B-1 a & b

Under given conditions of temperature and hydrogen ion concentration the oxygen dissociation curves of blood from different individuals do not vary greatly. A comparison of the data given in the following two charts with data obtained from the blood of three individuals is shown in Table I.

TABLE I

Comparison of Individual Oxygen Dissociation Curves

Arterial Oxygen Saturations in Percent of Oxygen Capacity (O_2-cap.) at pH = 7.40 (pCO_2 = 40 mm. Hg)

pO_2 mm. Hg	Blood of A. V. B. O_2-cap. = 20 vpc	Blood of G. S. A. O_2-cap. = 18 vpc	Blood of T. J. F. O_2-cap. = 17 vpc	Data in Charts (Dill)
10	15	11	13	14
20	40	34	36	35
25	50	46	—	47
30	60	59	57	58
40	76.5	77	73	74
50	86	87	84	84.5
60	91	91.5	90	89
70	94.5	95.5	93.5	93
80	96	97	96	95
100	98	98	98.5	97.5

Sources: 1) Curves based on data of D. B. Dill, Wright Field Aero-Medical Unit.

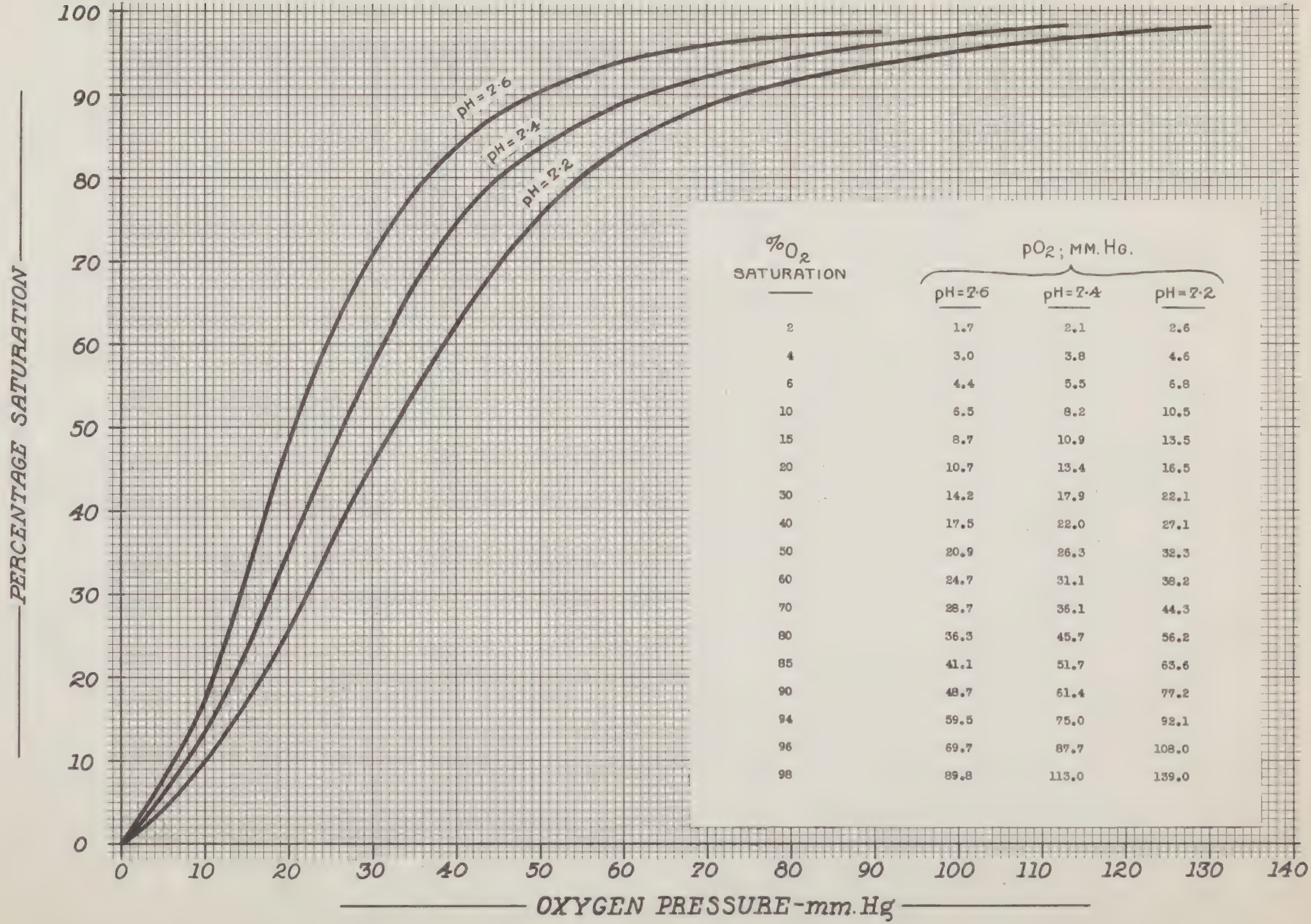
2) Bock, A. V. & Adair, G. S.—J. B. C. LIX 353 (1924).

3) Henderson, L. J.—*Blood* Yale University Press (1928) p. 132.

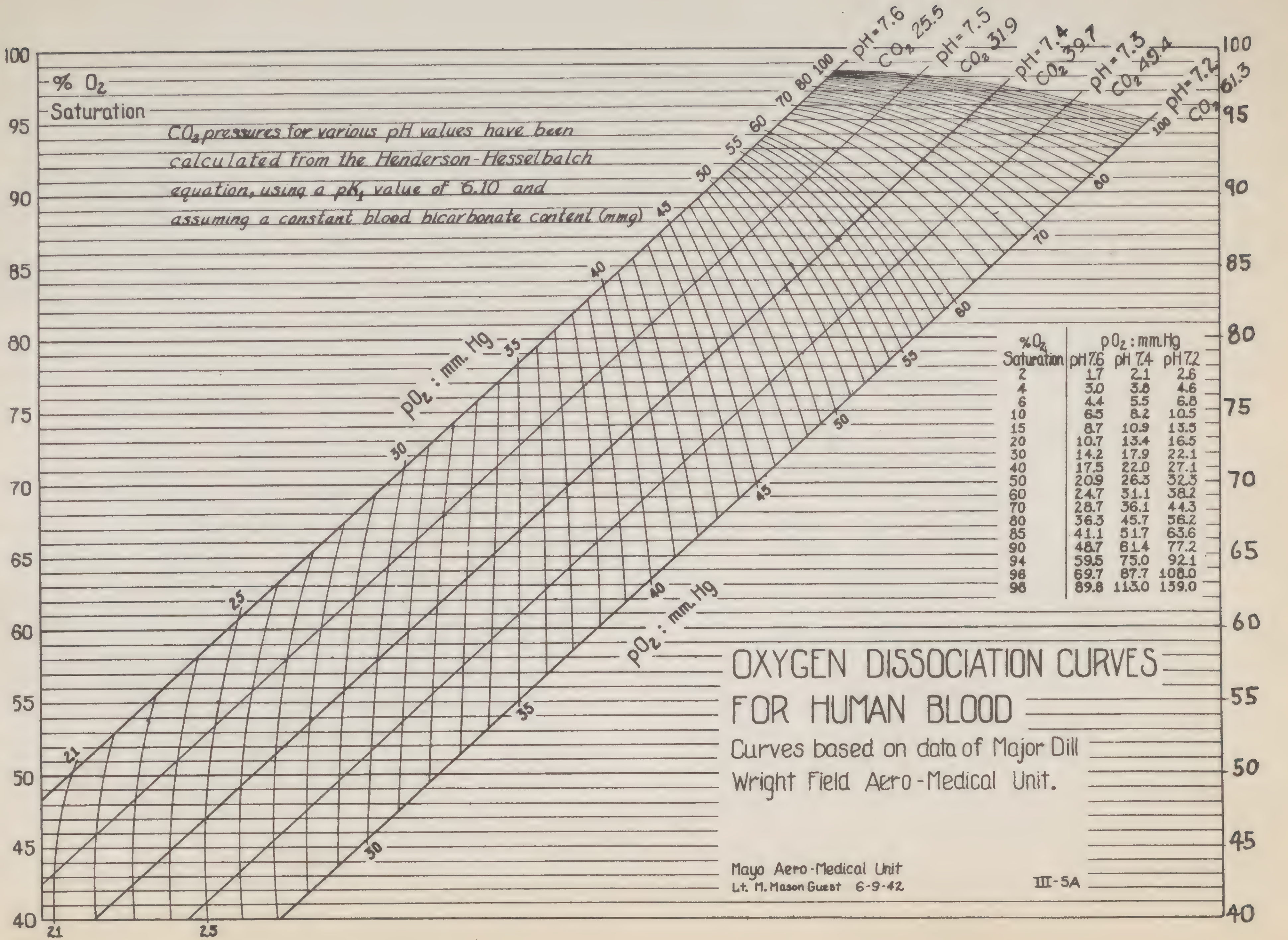
Prepared by

J. R. P.

OXYGEN DISSOCIATION CURVES FOR HUMAN BLOOD



$\%O_2$ SATURATION	pO_2; MM. HG. pH = 7·6	pH = 7·4	pH = 7·2
2	1.7	2.1	2.6
4	3.0	3.8	4.6
6	4.4	5.5	6.8
10	6.5	8.2	10.5
15	8.7	10.9	13.5
20	10.7	13.4	16.5
30	14.2	17.9	22.1
40	17.5	22.0	27.1
50	20.9	26.3	32.3
60	24.7	31.1	38.2
70	28.7	36.1	44.3
80	36.3	45.7	56.2
85	41.1	51.7	63.6
90	48.7	61.4	77.2
94	59.5	75.0	92.1
96	69.7	87.7	108.0
98	89.8	113.0	139.0



% O_2 Saturation	pO_2 : mm.Hg pH 7.6	pH 7.4	pH 7.2
2	1.7	2.1	2.6
4	3.0	3.8	4.6
6	4.4	5.5	6.8
10	6.5	8.2	10.5
15	8.7	10.9	13.5
20	10.7	13.4	16.5
30	14.2	17.9	22.1
40	17.5	22.0	27.1
50	20.9	26.3	32.3
60	24.7	31.1	38.2
70	28.7	36.1	44.3
80	36.3	45.7	56.2
85	41.1	51.7	63.6
90	48.7	61.4	77.2
94	59.5	75.0	92.1
96	69.7	87.7	108.0
98	89.8	113.0	139.0

OXYGEN DISSOCIATION CURVES FOR HUMAN BLOOD

Curves based on data of Major Dill
Wright Field Aero-Medical Unit.

Mayo Aero-Medical Unit
Lt. M. Mason Guest 6-9-42

III-5A

ARTERIAL OXYGEN SATURATION AT ALTITUDE

CHART B-3

November, 1943

Arterial Oxygen Saturation at Altitude

Chart B-3

Modified from *Physiology of Flight,*

Aero-Medical Laboratory, Wright Field. p. 13, Fig. 8

Explanation:

Open *circles* are data from gasometric analysis of arterial blood drawn by puncture. *Dots* are values obtained with the oximeter. Analytical errors of the two methods are approximately ± 1% and ± 5% saturation respectively. Subjects were seated at rest or engaged in light activity. Oximeter readings were average steady values obtained during a stay of at least ten minutes at any given altitude. Points obtained in the range 0-5000 feet have been omitted owing to doubt as to the validity of conventional methods for determining the oxygen saturation in this region. The normal arterial oxygen saturation as determined by gas analysis of blood drawn by puncture is usually stated to be 93-95%. Recent evidence indicates that this value is too low and that the true oxygen saturation of arterial blood at sea-level is 97-98%.

Qualitative indications of the handicap associated with any particular oxygen saturation ("appreciable," "considerable," etc.) are based upon the opinions of investigators rather than upon analytical data. The extent to which the arterial oxygen saturation may be reduced without impairing physiological functions varies considerably from one individual to another and in the same individual from day to day. There is evidence that interference with visual mechanisms may take place at arterial saturations as high as 92-3% (5000 feet breathing air). Most performance tests of the "pursuit meter" type do not indicate changes of performance until the saturation has dropped below 80-85%.

Limitations:

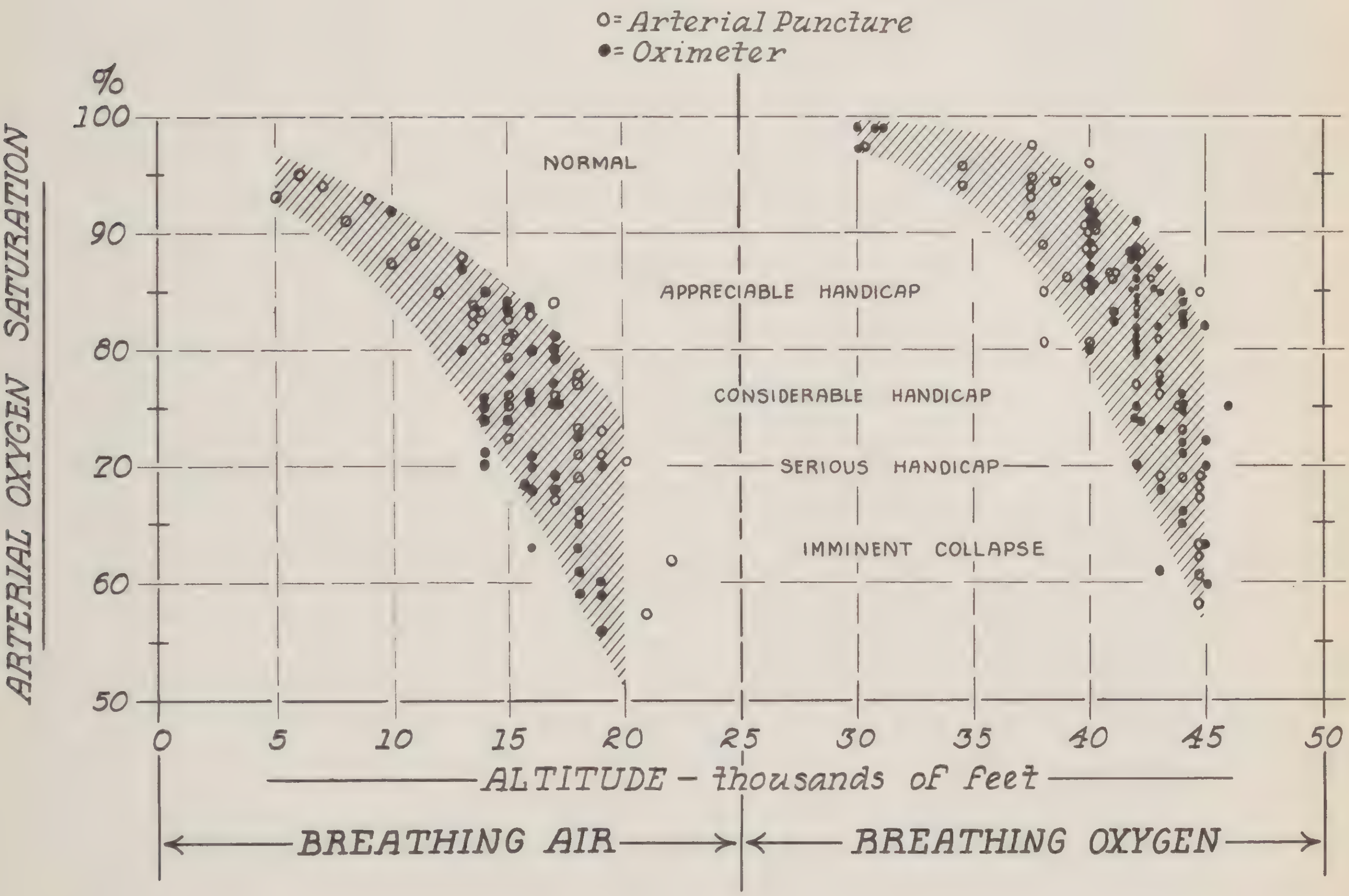
1) The data included in the chart were obtained from resting individuals. Evidence has been obtained by Dill, MR#EXP-M-54-653-39A Wright Field, June 10, 1941, that the data are also valid under conditions of light work (1500 ft-lbs/min., cf. Chart #R-3). Use of the data for heavier grades of work is not yet justified by experiment.

2) The observed scatter greatly exceeds the errors of analysis and, therefore, represents a real variation of arterial oxygen saturation among individuals at any given altitude. Due consideration of this scatter should be made in the application of mean values to any specific problem. There is evidence that the day to day variation of any one individual is considerably less than the scatter of the population. A statistical treatment of the data is given in a separate chart (#B-4).

Sources: a) Arterial puncture data—*Physiology of Flight* (cited above)
b) Oximeter data—Johnson Foundation, unpublished.

J. R. P.

ARTERIAL OXYGEN SATURATION AT ALTITUDE



ARTERIAL OXYGEN SATURATION AT ALTITUDE

STATISTICAL ANALYSIS
CHART B-4

Arterial Oxygen Saturation at Altitude

Statistical Analysis

Chart B-4

Use of Chart: Standards for problems involving arterial oxygen saturation as a function of altitude.

Explanation:

This chart depicts the variations of arterial oxygen saturation which occur among individuals breathing air or oxygen at selected altitudes. The data were taken from the points shown in Chart B-3 and are subject to the limitations outlined in that chart. The solid bars show the standard error of the mean and the cross-hatching shows the standard deviation about the mean. The central lines are drawn by eye as smooth curves which are as close as possible to the mean values at each altitude. Individual points are given where the data were considered too incomplete to warrant statistical treatment. Estimations of oxygen saturation made by the oximeter and by gas analysis of arterial blood are treated alike. Separate data are shown in Table II for altitudes at which five or more analyses by each method are available; the mean values obtained by the two methods are in close agreement except at one altitude (18,000 ft.). An important use of the data is the experimental verification of calculated "equivalent altitudes." It may be noted that equal arterial oxygen saturations breathing air and breathing oxygen are found at the same altitude "pairs" as those calculated on the basis of equivalence of alveolar gas composition in Chart A-2.

TABLE I

Mean Arterial Oxygen Saturation

Pressure Altitude	Total no. of subjects	Mean	Smoothed Mean	Standard Error of Mean	Standard Deviation
		Breathing air			
15,000 ft.	12	78.5%	78.3%	±1.1%	±3.6%
16,000	11	75.5	75.5	1.7	5.5
17,000	12	74.5	72.3	1.8	6.1
18,000	12	68.0	68.5	1.8	6.2
19,000	6	64.7	63.8	2.9	7.2
		Breathing oxygen			
40,000	16	88.0	88.5	1.0	4.0
41,000	5	85.0	85.8	0.8	1.8
42,000	15	83.4	82.3	1.9	7.5
43,000	14	77.4	78.1	1.7	6.5
44,000	14	74.7	73.5	2.0	7.5
44.8—45,000	13	67.6	68.2	2.2	7.9

TABLE II

Comparison of Oximeter and Arterial Puncture Data

Pressure Altitude	No. of subjects Oximeter	No. of subjects Puncture	Mean oxygen saturation Oximeter	Mean oxygen saturation Puncture
15,000	5	7	79.0 ± 1.8	78.0 ± 1.3
18,000	6	6	64.3 ± 1.9	72.1 ± 2.1
40,000	13	9	88.0 ± 1.5	88.0 ± 1.3
43,000	9	5	77.3 ± 2.9	77.6 ± 2.7
44.8—45,000	5	8	69.4 ± 3.8	66.5 ± 2.8

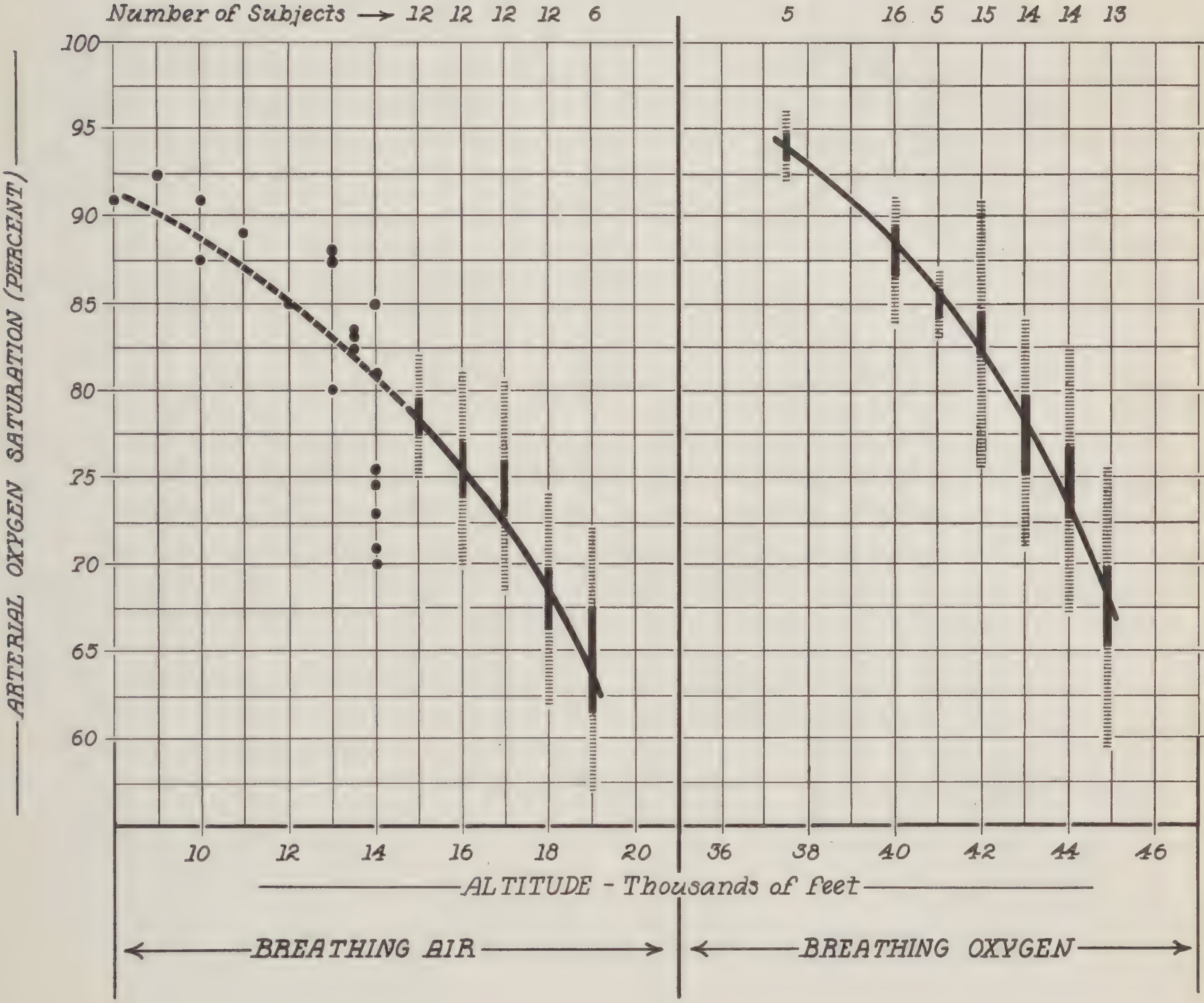
Limitations:

The data given in this chart may be useful as standards for discussions involving arterial oxygen saturation as a function of altitude. With the accumulation of new data, however, the present figures will almost certainly be subject to minor revision.

Source: Chart B-3

J. R. P.

ARTERIAL OXYGEN SATURATION AT ALTITUDE



SECTION E

Oxygen Supply Systems

November, 1943

Calculated Economies of Ideal Oxygen Systems

Charts No. E-1 a and No. E-1 b

Explanation:

These are calculated values of oxygen consumption. Because of factors of safety, manufacturing tolerances, and leaks, no actual system will give economies as good as those indicated. However, the curves do indicate the relative economies attainable by various systems if all are brought to the same degree of mechanical perfection.

Demand valve curves are based on the computation of components of respiratory volume as presented in Chart No. R-1. Diluter demand curves are based on the values of percentage oxygen for various equivalent altitudes as given in Chart No. A-2.

The curves for demand systems with rebreather are computed for a rebreather bag capacity of 35% of the tidal air volume. Experiments have shown that the economy changes very slightly with considerable increase of bag volume over this value.

The oxygen consumption indicated for the closed system with CO_2 absorber is assumed as .58 liters SPTD for a Respiratory Minute Volume of 15 liters BTPS. (See Chart R-2.) It should be noted that oxygen consumption in demand systems depends only on ventilation rate, while in closed systems it depends primarily on metabolic rate. There is a large spread in the ratio of ventilation rate to metabolic rate as shown in Chart R-2. The curve for the closed system is therefore not strictly comparable to those for the demand systems.

Definition of symbols:

Vr = Respiratory minute volume BTPS

Vo = Oxygen consumption from supply system per min. STPD

P_B = Barometric pressure, mm. Hg.

pH_2O = Vapor pressure of water

Fs = Fraction of inspired gas which comes from the oxygen supply system $= \dfrac{Fo_2 - .21}{.79}$

Fo_2 = Fraction of oxygen in inspired air required to produce desired equivalent altitude as obtained from Table P-2

T = Absolute temperature

Vb = Effective volume of rebreather bag (if any)

Vt = Average tidal volume

General equation used:

$$\frac{Vo}{Vr} = \frac{P_B - pH_2O}{760} \times \frac{273}{T} \times Fs \times \left\{ 1 - \frac{Vb}{Vt} \right\}$$

Specific equations used:

For demand systems:

$$\frac{Vo}{Vr} = \frac{P_B - 47}{760} \times \frac{273}{310}$$

For demand diluter systems:

$$\frac{Vo}{Vr} = \frac{P_B - 47}{760} \times \frac{273}{310} \times \frac{Fo_2 - .21}{.79}$$

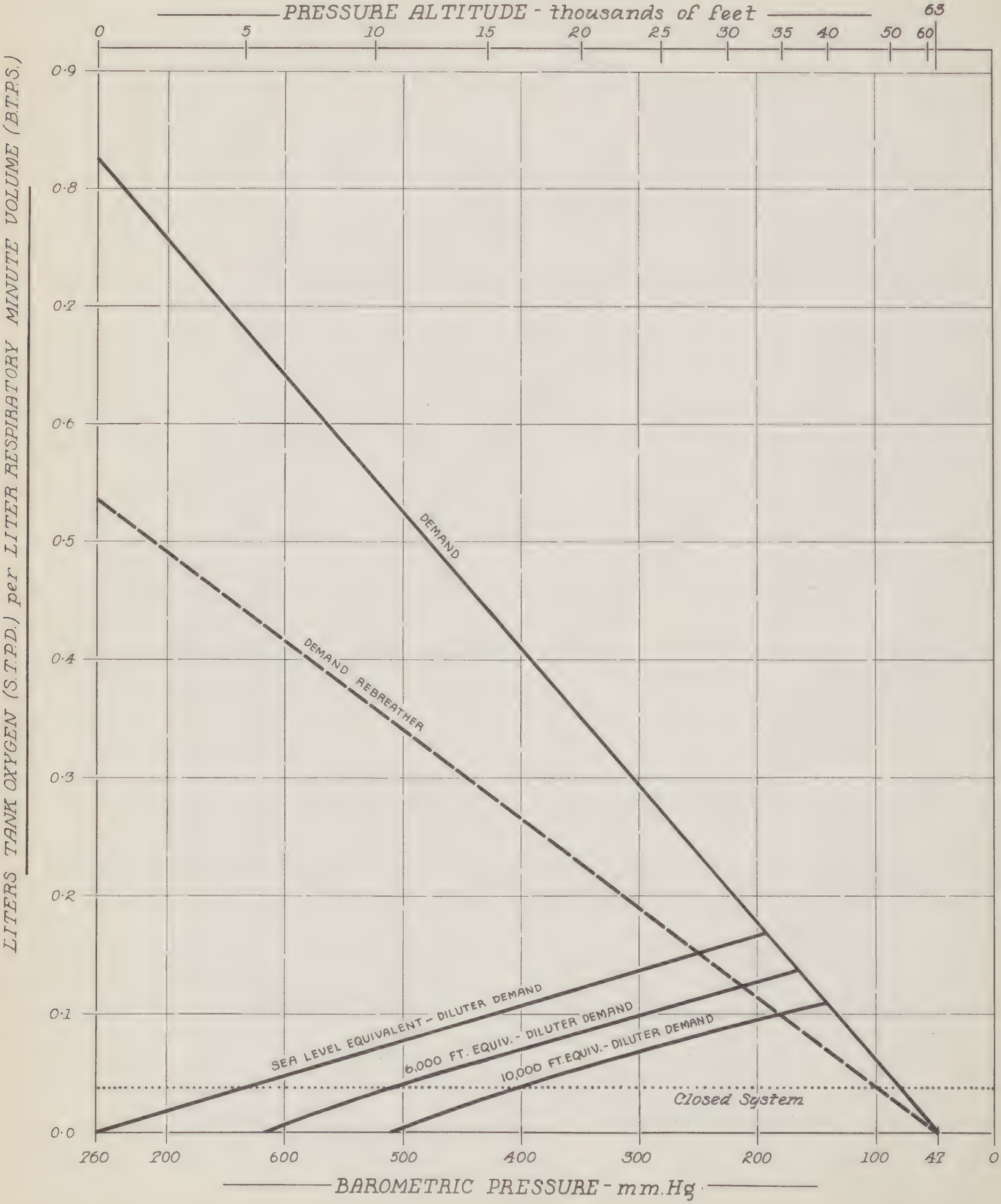
For demand diluter rebreather systems:

$$\frac{Vo}{Vr} = \frac{P_B - 47}{760} \times \frac{273}{310} \times \frac{Fo_2 - .21}{.79} \times 0.65$$

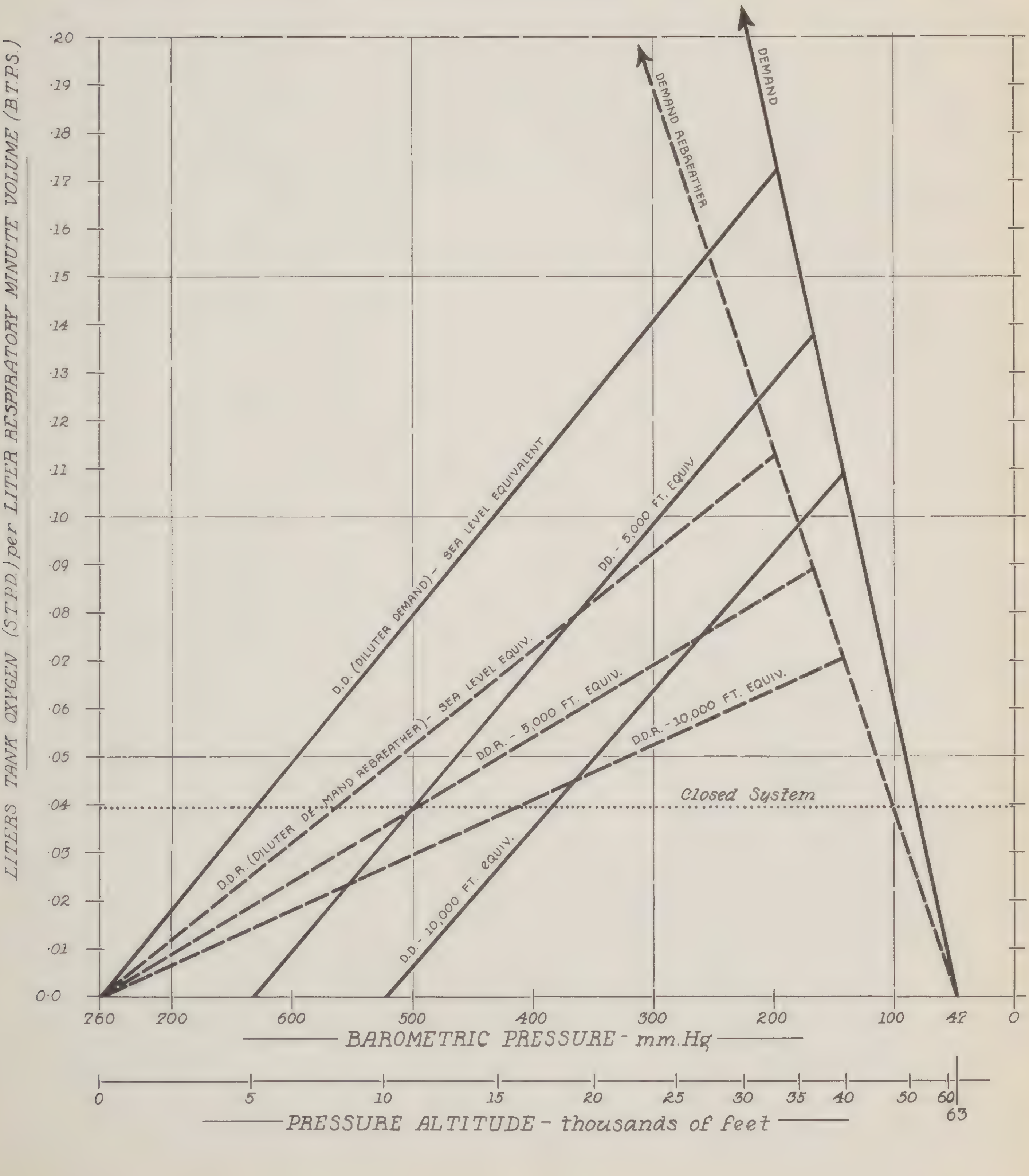
Source: Boothby, Special Report #1, August 4, 1942

A. J. R. and G. A. M.

CALCULATED ECONOMIES OF IDEAL OXYGEN SYSTEMS



CALCULATED ECONOMIES OF IDEAL OXYGEN SYSTEMS



SECTION M

Carbon Monoxide

EQUILIBRIA BETWEEN OXYGEN CARBON MONOXIDE
AND HEMOGLOBIN IN NORMAL HUMAN BLOOD

CHART M-1

Equilibria Between Oxygen, Carbon Monoxide and Hemoglobin in Normal Human Blood

Chart M-1

Symbols: $p(O_2)$ = partial pressure of oxygen in blood.
$p(CO)$ = partial pressure of carbon monoxide in blood.
$\%HbO_2$ = percentage of total hemoglobin in form of oxyhemoglobin.
$\%HbCO$ = percentage of total hemoglobin in form of carboxy-Hb.
K = Haldane constant.
F = a function defined by the oxygen dissociation curve of normal human blood at 37°C, pCO_2 = 40 mm. Hg.

The laws governing the equilibria between oxy-, carboxy- and reduced hemoglobin in the presence of known partial pressures of oxygen and carbon monoxide were first described by Douglas, Haldane & Haldane (1). The laws may be stated in the following way—

$$\frac{\%HbCO}{\%HbO_2} = \frac{Kp(CO)}{p(O_2)} \tag{1}$$

$$\%\ HbO_2 + \%HbCO = F[p(O_2) + Kp(CO)]$$

Equations (1) and (2) may be combined and solved for either HbO_2 or for HbCO. Thus—

$$\%HbO_2 = \frac{F[p(O_2) + Kp(CO)]}{pO_2 + KpCO} \times pO_2 \tag{3}$$

or

$$\%HbCO = \frac{F[p(O_2) + Kp(CO)]}{p(O_2) + Kp(CO)} \times KpCO \tag{4}$$

In normal human blood equilibriated with known values of p(CO) and $p(O_2)$ Douglas et al. found excellent agreement between the %HbCO found by analysis and the values obtained from equation (4). Further experimental evidence confirming the validity of the equations has recently been obtained by Roughton & Darling (2).

The curves shown in Chart M-1 are obtained from equation (3). A graphical solution of this equation may be made in the following way—

a) Let $y = p(O_2) + Kp(CO)$ (5)

From the oxygen dissociation curve of normal human blood (Chart B-1a) a graph is constructed relating F(y)/y to y. Sample values are given below—

Table I.

y	F(y)	F(y)/y
50	84.5	1.69
70	93	1.33
90	97.5	1.08

b) From equations (3) and (5),

$$F(y)/y = \%HbO_2/p(O_2) \tag{6}$$

For any given values of $\%HbO_2$ and $p(O_2)$, F(y)/y and hence y are determined.

Whence $Kp(CO) = y - p(O_2)$

c) Example: Let $\%HbO_2 = 80$, $p(O_2) = 60$ mm. Hg. Find Kp(CO).
From (6) F(y)/y = 80/60 = 1.33
From graph constructed in (a) or Table I we find that when F(y)/y = 1.33, y = 70.
Whence, KpCO = 70 — 60 = 10
If K = 210 (cf below), p(CO) = 0.0475 as shown in chart.

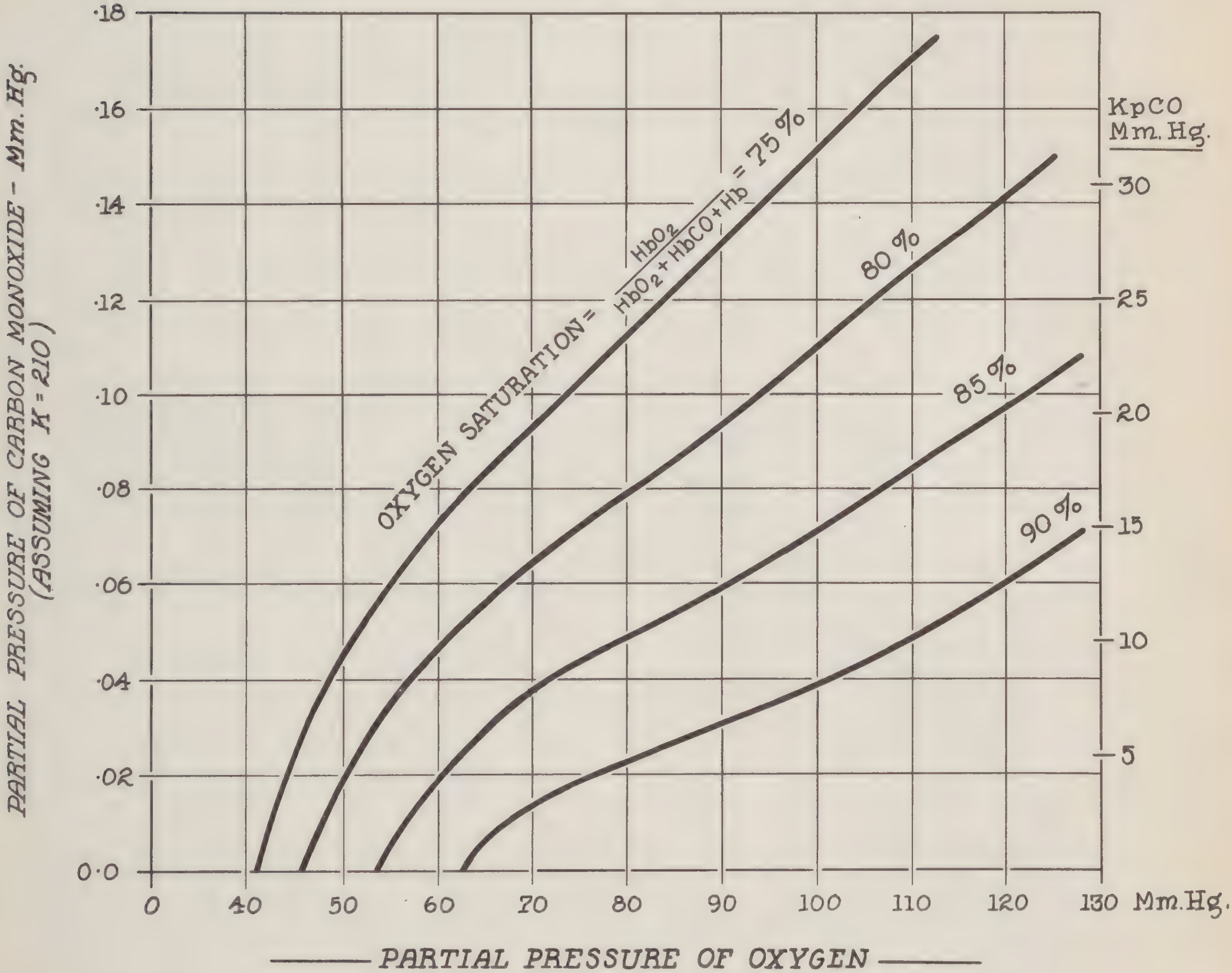
The Value of K:

The value of K for human hemoglobin has been variously reported to range from 200-290. However, Sendroy et al. (3) found an avearge value of 210 ± 5 in six individuals and this value has been employed in constructing the ordinates in the Chart.

Sources: 1) Douglas, Haldane & Haldane, J. Physiol. *44,* 275, 1912
2) Roughton & Darling, C. A. M. Report #93, 1942
3) Sendroy, Liu, & Van Slyke, Amer. J. Physiol. *90,* 511, 1929

J. R. P.

EQUILIBRIA BETWEEN OXYGEN, CARBON MONOXIDE AND OXYHEMOGLOBIN IN NORMAL HUMAN BLOOD.



November, 1943

STANDARDS FOR CARBON MONOXIDE

Chart M-2

I. *Definition of Symbols*

P_B = barometric pressure.
Po_2 = partial pressure of oxygen in dry inspired air.
Pco = partial pressure of CO in dry inspired air.
$p(O_2)$ = partial pressure of oxygen in arterial blood.
p(CO) = partial pressure of CO in arterial blood.
p(CO)i = partial pressure of CO in arterial blood, initially.
pCO = partial pressure of CO in alveolar air.
k = time constant of rate of uptake of CO by the blood.
t = time in hours required to reach dangerous p(CO).

II. *Equilibrium Conditions*—Concentrations of CO in dry inspired air required to bring the arterial oxygen saturation to 85% at different altitudes.

The p(CO) required to bring HbO_2 to 85% at any given $p(O_2)$ is shown in Chart M-1. The altitude corresponding to any given $p(O_2)$ and the % CO in dry inspired air corresponding to any given p(CO) and altitude determine the curve marked "indefinitely" in Chart M-2. The values were obtained in the following way—

A. *pO_2 as a function of altitude.* The exact relations between $p(O_2)$ and altitude are unknown. The $p(O_2)$ in arterial blood calculated in the conventional way from the arterial oxygen saturation (Chart B-1a) is less than that in alveolar air by an amount which decreases with decreasing oxygen saturation (Table I). The values chosen for the preparation of Chart M-2 were calculated from the average arterial oxygen saturations at different altitudes (Chart B-3); they are shown in Table I.

TABLE I

VALUES OF pO_2 USED IN CONSTRUCTION OF CHART M-2

Altitude—breathing air (Ft.)	Po_2 in dry inspired air	Alveolar pO_2 (Chart A-1)	Arterial $p(O_2)$—values used for Chart M-2
0	159	103	87
2000	148	94	83
4000	137	85	78
6000	127	76	69
8000	118	66	62
10000	109	57	55
12000	101	50	49

Continued on back of Chart M-2

Standards for Carbon Monoxide

Chart M-2

Factors Considered

1) Equilibrium values of oxyhemoglobin in the presence of known partial pressures of oxygen and carbon monoxide.
2) Pressure of oxygen in arterial blood as a function of altitude.
3) Equilibrium relations between the partial pressure of carbon monoxide in alveolar air and in dry inspired air.
4) The rate at which carbon monoxide enters the blood as affected by the respiratory minute volume and the concentration in dry inspired air.
5) The effects of initial concentrations of carbon monoxide in the blood.

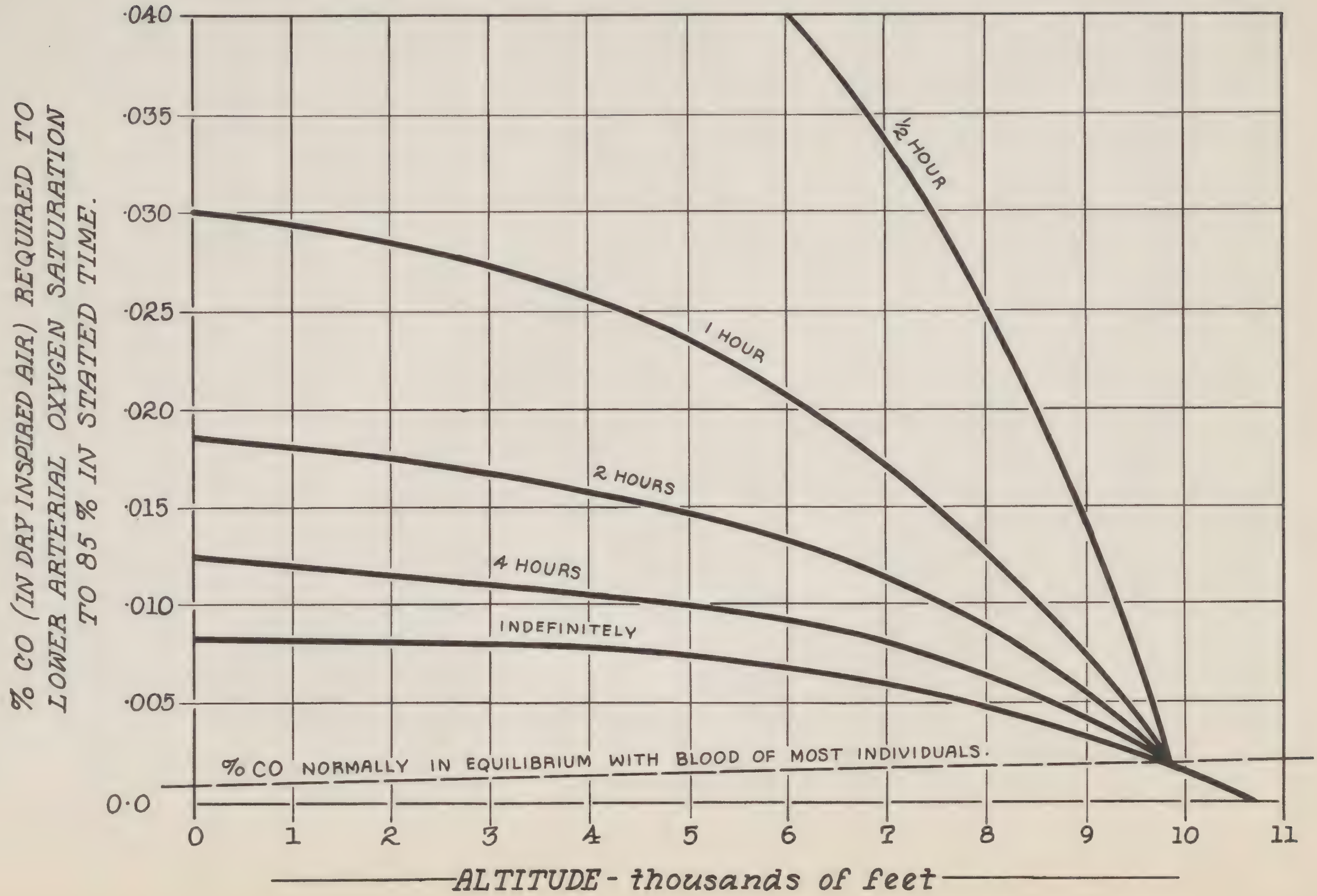
Limitations of Chart M-2: The standards for CO shown in Chart M-2 depend largely upon the choice of numerical values for 3 physiological variables.

1) Choice of 85% saturation as that value which may be safely tolerated: This value corresponds approximately with that which obtains while breathing air free from CO at 12,000 ft. (Chart B-4). The exact value chosen critically affects the calculated standards. Thus if 88% HbO_2 is chosen instead of 85% the permissible CO at 6,000 ft. would be reduced from 0.0065% to 0.0041%.

2) Choice of values of pO_2 as a function of altitude:—Recent evidence indicates that $p(O_2)$ may be considerably nearer to alveolar pO_2 at all altitudes than has been assumed in the construction of the Chart (Table I above). If this is in fact the case then the permissible CO at lower altitudes may considerably exceed the values shown in the Chart. Thus at sea-level 0.013% CO instead of 0.0083% would be required to bring HbO_2 to 85%.

3) Time standards: If the respiratory minute volume exceeds 10 liter/min. then the rate of uptake of CO may exceed the standards shown in the chart. A margin of safety should be provided under conditions in which prolonged activity is expected. The margin of safety should be proportional to the percentage increase in minute volume (cf. Chart R-3).

STANDARDS FOR CARBON MONOXIDE



B. *%CO in dry inspired air as a function of pCO.*

At equilibrium CO is neither taken up nor given off by the blood; under these conditions pCO = p(CO) and the ratio p(CO)/Pco is the same as that for nitrogen or for any other neutral gas (Haldane & Smith (3)).

$$p(CO)/P_{CO} = pN_2/P_{N_2} \tag{1}$$

The value of this ratio is defined by Equations (4) and (9) in the Essay on "Composition of Respiratory Gases" in this manual. Solving Equations (1) above, and (4) and (9) in the Essay, we have,

$$\frac{p(CO)}{P_{CO}} = \frac{P_B - 47}{P_B} + \frac{pCO_2\,(1 - RQ)}{P_B \times RQ}$$

whence,

$$\%CO = \frac{P_{CO} \times 100}{P_B} = \frac{100\,p(CO)}{P_B - 47 + \dfrac{pCO_2\,(1 - RQ)}{RQ}} \tag{2}$$

For practical purposes variations of pCO_2 and RQ have a negligible effect (less than 1%) on the % CO calculated from (2). Using nominal values of $pCO_2 = 39$ mm. Hg and R. Q. = 0.85 (2) becomes—

$$\%CO = \frac{100\,p(CO)}{P_B - 40} \tag{3}$$

and this form was used in the preparation of Chart M-2.

Sample Calculation: What concentration of CO is required to bring HbO_2 to 85% at 6000 ft.? Reference to Table I shows that at this altitude pO_2 in arterial blood is 69 mm. Hg. Reference to Chart M-1 shows that this corresponds with a blood p(CO) of 0.03 mm. Then from (3) we have—

$\%CO = 100 \times .037/609 - 40 = 0.0065$ *Ans.*

IV. *Dynamic Conditions:* The rate at which CO is taken up by the blood.

The uptake of CO by the blood may be expressed by the exponential equation—

$$\log \frac{P_{CO} - p(CO)i}{P_{CO} - p(CO)} = kt \tag{5}$$

Under conditions of light activity (respiratory minute volume 10 L./min.) the value of k is approximately 0.12 when t is expressed in hours. Thus 90% of the experimentally obtained values of Forbes et al. (2) lie within the boundary defined by this equation.

Example: How many hours are required to reduce the arterial oxygen saturation to 85% while breathing 0.02% CO at 6000 ft.?

a) $P_{CO} = \%CO \times P_B = 0.02\% \times 609 = 0.122$ mm. Hg

b) $p(O_2)$ at 6000 ft. is 69 mm. Hg (Table I above)

c) p(CO) (when $pO_2 = 69$, $HbO_2 = 85\%$) is 0.038 mm. Hg (Chart M-1)

d) Assume p(CO)i = 0.01 mm. (usual in blood of cigarette smokers)

whence, $\log \dfrac{.122 - .010}{.122 - .038} = .12\,t$ whence t = 1.05 hours *Ans.*

Sources: 1) Chart M-1

2) Forbes, Sargent & Roughton, C. A. M. Report #97 (1942)

3) Haldane & Smith, J. Physiol. *20,* 497 (1896)

J. R. P.

CARBON MONOXIDE STANDARDS FOR USE WITH
AUTO-MIX SYSTEMS

CHART M-3

November, 1943

Carbon Monoxide Standards for Use With Auto-Mix Systems

Chart M-3

The use of an Auto-mix system alters the standards shown in Chart M-2 in two ways—

1) Alteration of Po_2 in inspired gas as a function of altitude.

2) Alteration of fraction of inspired gas breathed from cabin and containing carbon monoxide.

Calculations:

1) For any given value of Po_2 the value of p(CO) required to bring HbO_2 to 85% saturation was calculated as in Chart M-2. The %CO corresponding to each value of p(CO) at any altitude is then,

$$\%CO = \frac{100\,p(CO)/f}{P_B - 40} \qquad (1) \text{ cf. Equation (3) Chart M-2}$$

where f is the fraction of cabin air in inspired air. But,

$$f = \frac{(1 - Fo_2)}{(1 - .21)} = 1.26\,(1 - Fo_2) \qquad (2)$$

Combining (1) and (2) we have,

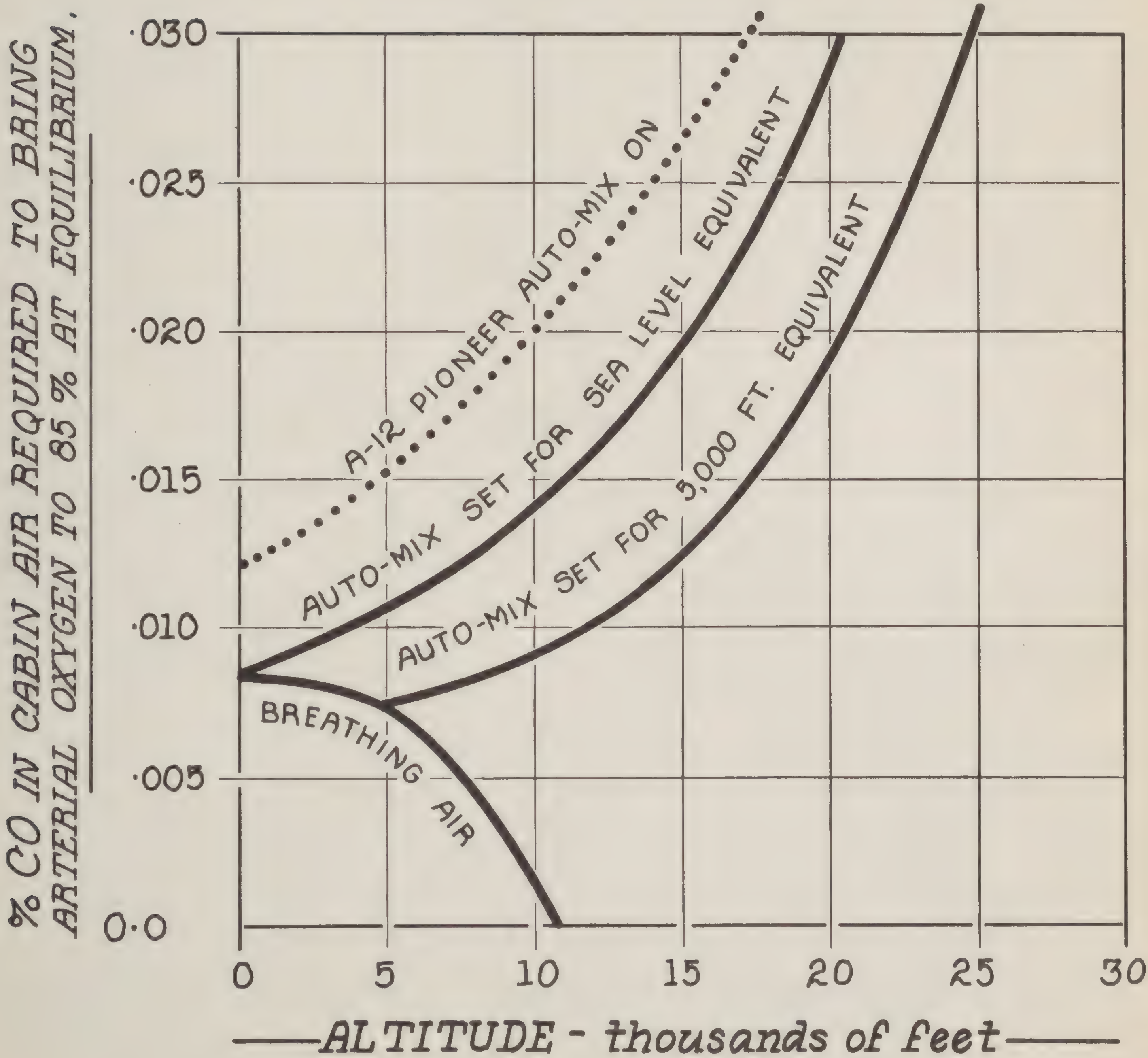
$$\%CO = \frac{100\,p(CO)}{P_B - 40} \times \frac{1}{1.26(1 - Fo_2)}$$

The values of Fo_2 used for the chart are shown in the following table—

Altitude	A-12 Pioneer Regulator	Ideal-Regulator Sea-level Equiv.	Ideal Regulator 5000 ft. Equiv.
0	.35	.21	.21
5000	—	.25	.21
10000	.41	.31	.27
15000	—	.39	.33
20000	.60	.49	.41
25000	—	.63	.52

J. R. P.

CARBON MONOXIDE STANDARDS FOR USE WITH AUTO-MIX SYSTEMS.



SECTION C

Circulation